NISTIR 5092

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology

NIST

Electronics and Electrical Engineering Laboratory

Radio-Frequency Technology Division

Programs, Activities, and Accomplishments

The Electronics and Electrical Engineering Laboratory

Through its technical laboratory research programs, the Electronics and Electrical Engineering Laboratory (EEEL) supports the U.S. electronics industry, its suppliers, and its customers by providing measurement technology needed to maintain and improve their competitive position. EEEL also provides support to the federal government as needed to improve efficiency in technical operations and cooperates with academia in the development and use of measurement methods and scientific data.

EEEL consists of five programmatic divisions and two matrix-managed offices.

- Electricity Division
- Semiconductor Electronics Division
- Radio-Frequency Technology Division
- Electromagnetic Technology Division
- Optoelectronics Division
- Office of Microelectronics Programs
- Office of Law Enforcemnent Standards

This document describes the technical programs of the Radio-Frequency Technology Division. Similar documents describing the other Divisions and offices are available. Contact NIST/EEEL, 100 Bureau Drive, MS800, Gaithersburg, MD 20899-8100, Telepone: 301.975.2220. On the Web: www.eeel.nist.gov.

The Cover symbolizes the diverse programs of the Radio-Frequency Technology Division and the cross section of industry that it serves. The programs range from the development of new metrology for microelectronics devices and circuits for radio and high speed digital applications, to the precise characterization of electromagnetic fields, wireless systems, and antennas for radar and for satellite and terrestrial communications.

Electronics and Electrical Engineering Laboratory

Radio-Frequency Technology Division

Programs, Activities, and Accomplishments

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January 2000

U.S. DEPARTMENT OF COMMERCE
William M. Daley, Secretary

Technology Administration
Dr. Cheryl L. Shavers, Under Secretary of Commerce for Technology

National Institute of Standards and Technology
Raymond G. Kammer, Director

Contents

Welcome

The Radio-Frequency Technology Division is a critical national resource for a wide range of customers. U.S. industry is the primary customer for both the Division's measurement services and for technical support on the test and measurement methodology necessary for research, product development, manufacturing, and international trade. The Division represents the U.S. in international measurement intercomparisons and in standards development related to radio-frequency and microwave technology and electromagnetic fields. The Division also provides measurement services and expert technical support to other agencies of the Federal government to support their programs in domestic and international commerce, in national defense, in transportation and communication, in public health and safety, and in law enforcement.

This book will describe our many and diverse projects. However before you begin, I would like to briefly describe our mission, our programs, and our organization.

Mission

To provide the national metrology base for characterization of the electromagnetic properties of components, materials, systems, and environments, throughout the radio spectrum.

Division Function

The Division:

- Enhances national competitiveness by providing metrology resources to facilitate development and commercialization of a broad range of radio-frequency electronic and electromagnetic technologies;
- Develops theory, techniques, systems, and standards for measurement of electromagnetic and other essential properties of components, materials, environments and systems throughout the radio spectrum;
- Provides for national and international measurement harmony and formal traceability via calibration services, reference standards, and measurement intercomparisons;
- Disseminates research results via archival publications, conference presentations, workshops, courses, and external interactions. Programs typically address fundamental measurement problems of interest to a broad industrial cross-section and of sufficient difficulty that resources are generally not available elsewhere to solve them; programs leverage internal resources with resources from other government agencies, industry and academia, and endeavor to meet the most critical industrial and governmental needs.

Our Technical Programs

The Division carries out a broad range of technical programs focused upon the precise realization and measurement of physical quantities throughout the radio spectrum. Key directions include: (a) the development of artifact reference standards, services and processes with which industry can maintain internationally recognized measurement traceability, (b) the advancement of technology through the development of new measurement techniques that are theoretically and experimentally sound as well as relevant and practical, (c) the assessment of total measurement uncertainties, and (d) the provision of expert technical support for national and international standards activities. We strive to perform leading-edge metrology research of high quality that is responsive to national needs. The radio-frequency spectrum ranges from above audio to below the far infrared. The programs range from measurements for microelectronics devices and circuits for radio and high speed digital applications, to the characterization of electromagnetic fields, wireless systems, and antennas for radar and for satellite and terrestrial communications.

Division programs cover the following technical areas:

Fundamental Microwave Quantities
The Fundamental Microwave Quantities Program develops metrology for measuring impedance, scattering parameters, attenuation, power, voltage, and thermal noise; and provides essential measurement services to the nation.

High-Speed Microelectronics
The High-Speed Microelectronics Program develops measurement techniques for the radio-frequency electromagnetic characterization of microelectronic structures and devices, on-wafer.

Electromagnetic Properties of Materials
The Electromagnetic Properties of Materials Program develops theory and methods for the measurement of the dielectric and magnetic properties of bulk and thin-film materials throughout the radio spectrum.

Wireless Systems
The Wireless Systems Program has three thrusts: the proactive development of standards for broadband wireless access, the characterization of the nonlinear properties of devices and circuits, and the characterization of passive inter-modulation products.

Antenna and Antenna Systems
The Antenna and Antenna Systems Program develops theory and techniques for the measurement of gain, pattern, and polarization of advanced antennas, for the measurement of the gain and noise of large antenna systems, and for the measurement of radar cross section.

Electromagnetic Compatibility
The Electromagnetic Compatibility Program develops theory and methods for establishing precise measurements of electromagnetic field quantities and for characterizing the emissions and susceptibility of electronic devices and products.

The Division structure consists of two branches, called Groups, and the N-WEST program. The Group programmatic division is primarily between measurements for guided-wave technologies and for free-space electromagnetic-field technologies. The Groups, and their managers are:

RADIO-FREQUENCY ELECTRONICS GROUP : Conducts theoretical and experimental research to develop measurement standards and techniques, traceability resources, and special measurement "tools" necessary for advancement of both conventional and microcircuit guided-wave technologies; for characterization of active and passive devices and networks; and for measurement of power, noise, impedance, material properties, and other basic quantities.

Group Leader: Robert Judish
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RADIO-FREQUENCY FIELDS GROUP : Conducts theoretical and experimental research necessary for the accurate measurement of free-space electromagnetic field quantities; for characterization of antennas, probes and antenna systems; for development of effective methods for electromagnetic compatibility assessment; for measurement of radar cross section and radiated noise; and for measurement traceability of essential parameters.

Group Leader: Andrew Repjar
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The Division is also exploring new directions for the advancement of broadband wireless technology via standards development and system measurements.

N-WEST Program
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We hope that this collection of information will provide a useful resource for understanding the work of the Division and for making use of the technical capabilities and services that we provide for industry, government, and academia. We also invite you to visit our web site at: http://www.boulder.nist.gov/div813/. This site will provide you with current updates on our projects as well as our measurement-related software and many of our publications that can be downloaded.

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Fundamental Microwave Quantities

Power and Voltage

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Staff-Years:
2.4 professionals
3.25 technicians
1.0 guest scientists

Funding Sources:
NIST (40%)
Other (60%)

"We are getting more and more requests for power calibrations in the 2.4 mm connector. I am pleased that NIST is developing the 2.4 mm CN mount and the calibration capability."

Tom Kawabata
Raytheon Systems

Project Goals

Develop coaxial and waveguide power standards, microcalorimeters, measurement techniques, and automated instrumentation that support and provide the calibration services for power transfer standards. Enhance power and voltage services through system development, improved transfer standards and new measurement techniques. Provide calibration services to industry in power and voltage. The frequency range is from 10 kHz to 110 GHz, depending on the specific measurement service.

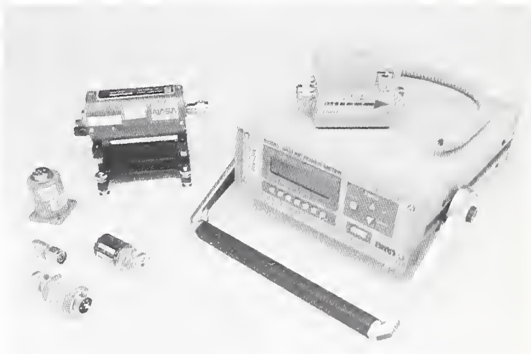
2.4 mm microwave calorimeter and detector.

Customer Needs

The development and maintenance of RF standards and calibration systems for power and voltage measurements impact most manufacturers and users of electrical/electronic instrumentation. The greatest area of impact is in supplying standards, calibrations and/or measurement methods to the manufacturers and users of the instrumentation. These calibration services insure that the devices and systems operate within their specifications. For manufacturers the calibration services are important for their domestic and international marketing success. The calibration services also impact the design and development of new electronic devices and guarantee the performance of a variety of electronic components.

Technical Strategy

The measurement of microwave power is one of the most fundamental parameters in RF measurements. It is necessary for the determination of output levels of signal generators, radio and television transmitters and all types of radar and wireless communication sources. Power measurements are also fundamental to the measurement of the signal-to-noise ratio of communication systems. Systems that are overdesigned, because of inaccurate power measurements, are expensive and non-competitive. All commercial applications of microwave energy, including communications, navigation, surveillance, manufacturing, aerospace, and medicine, require accurate measurement of microwave energy. The overdesign of products is costly, while the incorrect measurement of power can lead to system failure. International marketing of U.S. microwave instrumentation and devices requires power standards that are recognized and accepted by the international community.



Microwave power meter and detectors

The microwave industry is rapidly expanding into frequencies above 10 GHz. In support of this development, NIST is developing new coaxial power standards and measurement capabilities. The 2.4 mm power standard operates over a frequency range of 0.05 GHz to 50 GHz and NIST now has a measurement capability over this entire range. In addition to operating at higher frequencies, the 2.4 mm standard offers a reduced uncertainty in power measurements. The 2.4 mm detector will also be used as a standard to provide calibration services in other connector sizes such as 2.92 mm.

"Recent changes in FCC rules regarding measurement of harmonic and spurious content through the fifth harmonic for certified devices has put new pressure on power calibration standards above 95 GHz. These rules were apparently approved in the absence of power calibration standards above 95 GHz."

Chuck Oleson
Oleson Microwave Labs

MILESTONE: By 2000, complete the development of 2.4 mm standards and provide a calibration service for 2.4 mm thin-film, thermistor, and thermoelectric detectors over a frequency range of 0.05 to 50 GHz.

The 0.05 to 50 GHz direct-comparison measuring system provides state-of-the-art power measurement capability. The new system is faster and more accurate than any other system currently available. This direct-comparison system replaces the need for the multiple standards and measuring systems that operated in much narrower frequency ranges with one standard and one operating system. Two systems are operational; one is in use at the Navy Primary Standards Laboratory in San Diego, California and the other is at NIST.

Milestone: By 2001, evaluate and deliver 0.05-50 GHz direct comparison power calibration system to the Air Force.

The 3.5 mm calibration service is currently limited to the 2-26 GHz frequency band in 1 GHz increments. This service is provided through the use of characterized adapters and two measurement systems. Use of the new 2.4 mm system provides the opportunity for significant improvement in the 3.5 mm calibration service. The new service will provide expanded frequency coverage in 3.5 mm power calibrations. The expanded service will operate over the frequency range of 0.05 to 33 GHz in 0.1 GHz increments. Initially, the service will be offered up to 26.5 GHz and later extended to 33 GHz. In addition to the greater frequency coverage, the new service will offer a reduced uncertainty.

Milestone: By 2000, provide an expanded and more accurate calibration service for 3.5 mm coaxial connectors over a frequency range of 0.05-33 GHz.

Foreign national measurement institutes in developing industrial countries seek NIST support in establishing measurement capabilities. Microwave power is basic and that capability is needed in order to measure other microwave quantities. NIST facilitates world-wide harmonization by providing support to developing nations.

MILESTONE: By 2001, test, calibrate and deliver Type N calorimeter, standards and measurement system to Singapore.

Develop new waveguide power standards for use over the frequency range from 8 to 110 GHz

MILESTONE: By 2000, evaluate the changes in effective efficiency and reflection coefficient due to reduction of electromagnectic leakage in modified WR-22 mounts.

An important component in the maintenance of the units of RF power and voltage at NIST is participation in international comparisons. Through this link to the international community NIST insures that its capabilities in the measurement of power and voltage and the units that are maintained are comparable to other national measurement institutes. This relationship insures that the users of NIST calibration services will be able to compete in the international market.

Milestone: By 2000, continue to measure and circulate WR-22 transfer standards. As the pilot laboratory, compile and publish the results of the WR-22 comparison.

Milestone: By 2000, complete measurements , analyze results, and send report to the pilot laboratory for GT-RF 92-6, the measurement of voltage in the frequency range 1-1000 MHZ.

Besides measuring power over an expanding frequency range there is a need for calibration of power standards at higher power levels. NIST has developed a high-power measurement system at power levels from 10 to 1000 watts for the frequency range 10 MHz to 1 GHz. The high-power standards are quite cumbersome, and ideally, all measurements needed to characterize them should be done on a single system. The integration of auxiliary measurements into the basic high-power system will reduce the time needed to calibrate these standards.

MILESTONE: By 2000, add reflection coefficient measurement capability to system using commercial vector network analyzer.

Voltage standards in the range 1 to 200 volts and in the frequency range 100 kHz to 100 MHz serve as a basic testing tool for many manufacturers and users of RF instrumentation. The NIST calibration service and standards to support these measurements have been active for approximately forty years. The NIST primary standards were initially calibrated at the start of the service. Since that time, although there have been numerous comparisons with other standards both domestic and international to insure their stability, the primary standards have not been recalibrated. Using state of the art ac and dc sources, and with some redesign of the measurement circuitry, the uncertainties in these measurements can be reduced.

MILESTONE: By 2000, complete modifications of measurement system, recalibrate NIST primary standards and issue new uncertainties.

Accomplishments

- Completed the direct comparison power system for the U.S. Navy Primary Standards Laboratory. The system was delivered to the Navy labs in San Diego, CA. This system measures thermistor, thin-film, thermoelectric, and diode power meters over a frequency range of 0.05 to 50 GHz. Navy personnel were trained on the use of the system.

- Low-frequency evaluation measurements were made on the 2.4 mm microcalorimeter from 50 MHz through 1 GHz. This completes the full-band evaluation, providing the microcalorimeter correction factor, with its uncertainty, from 50 MHz to 50 GHz.

- The capability for measuring thermoelectric and diode power meters was added to the NIST 2.4 mm direct comparison system. Tests were conducted on various thermoelectric and diode power meters to assess the accuracy of those measurements. Preliminary indications are that NIST will be able to offer a calibration service for 2.4 mm thermoelectric power meters in the near future. Calibration of diode power meters, however, will be discouraged due to the higher uncertainty in those measurements.

- A NIST 2.4 mm coaxial direct-comparison power calibration system (to 50 GHz) has been developed and evaluated. The uncertainty analysis for the 2.4 mm direct-comparison power system has been completed. A summary of the analysis has been prepared. A measurement service is now being offered and the documentation for the system has been completed.

- A study was completed on the effects of RF leakage in waveguide thermistor power detectors. The study showed that RF leakage is a significant problem above 30 GHz in waveguide thermistor power standards. The leakage results in a systematic error that cannot be corrected. Experiments have been completed on methods to reduce the RF leakage.

- A new measurement service for high-power wattmeters was established. This service operates up to 1kW, and covers the frequency range from 2 to 1000 MHz. A high-power calibration system (10 to 1000 watts, 10 to 1000 MHz) has been developed and evaluated, and the documentation of the system has been completed. Two transfer standards have been calibrated and delivered to the Air Force.

- NIST recently participated in a BIPM international comparison, GT-RF/97-3, for microwave power. Measurements were made on WR-10 power sensors at 75 GHz and 94 GHz. A final report of the measurements has been completed.

- The evaluation of the WR-22 microcalorimeter was completed with aid of an additional full-band automated source. The expanded uncertainty is 0.8 percent.

- A modified transfer standard with less microwave leakage and a better connect technique improved the WR-15 microcalorimeter measurement repeatability. This has resulted in a reduction in the Type A uncertainty.

- NIST is the pilot laboratory for an international comparison, (GT-RF/97-2), of WR-22 power standards from 33 to 50 GHz. The transport standards have been measured by 4 of the 5 participants and are now waiting to be shipped to the last laboratory participating in the comparison.

- We measured the effective efficiency and reflection coefficient of a WR-15 mount at 62 GHz as part of an international comparison.

- A new automated voltage measurement system for high frequency thermal voltage converters (1.0 - 7.0 volt, 1 - 1000 MHz) has been designed, developed and evaluated. This calibration system will reduce uncertainties in this measurement by approximately 50%. The documentation for the system is nearly completed.

- A new voltage measurement system for calibrating micropotentiometers (1 μV- .1 volt, 1 MHz-1000 MHz) has been developed and evaluation of the system is approximately 50% completed.

- Participated in the BIPM international comparison (GT-RF/92-6) for high frequency voltage. Measurements were made between 10 to 1000 MHz on a high-

frequency thermal voltage converter and a power sensor-meter combination. A final report of the measurements has been completed.

- Calibrated 197 devices.

Fundamental Microwave Quantities

Scattering Parameters and Impedance

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Staff-Years:
0.9 professionals
1.25 technicians

Funding Sources:
NIST (60%)
Other (40%)

Project Goals

Provide traceability for microwave measurements in scattering parameters, impedance, and attenuation. Support the microwave industry by developing standards and new measurement techniques. Develop methods for assessing and verifying the accuracy of automatic network analyzers.

Commerical vector network analyzer

Customer Needs

Vector network analyzers (VNAs) are the single most important instrument in the microwave industry. These instruments are commonly found on production lines, in calibration laboratories, and in research laboratories. Vector network analyzers are typically calibrated daily, and the accuracy of their measurements can vary significantly after a calibration depending on the operator skills, the quality of the calibration standards, and the condition of the test ports. The microwave industry needs cost-effective techniques to monitor and verify the accuracy of VNA measurements. In addition, industry requires validation of techniques and procedures they develop. NIST supports these needs by providing consultations on measurement techniques and uncertainty characterization. We also offer an extensive array of measurement services that provide evidence of traceability and confidence to the customer.

Technical Strategy

New connectors are being used in instrumentation and cables, as the communication industry develops applications at higher frequencies. Support is needed for new connector interfaces.

MILESTONE: By 2002, add calibration services for systems in currently unsupported connector types (i.e., 75 ohms, SMA, SMP, 1.85 mm).

The Department of Defense calibration and standards laboratories require state-of-the art systems to support their measurement capability. Historically, NIST has provided them with dual six-port systems that measure the scattering parameters of passive devices. In addition to scattering parameter measurements, these systems can be used to calibrate power transfer standards.

MILESTONE: By 2000, complete construction of a 0.01-1000 GHz dual six-port for the Army Primary Standards Laboratory.

Our calibration customers have long expressed concerns over the cost of calibration services. Traditional calibration services for scattering parameters are used by the customer to verify their measurement capability. NIST is developing a cost-effective, alternative service in which NIST-owned measurement artifacts are sent to the customer for measurement in their laboratory. Their data are returned to NIST where the results are analyzed. A report comparing their measurements to NIST's is sent to the customer. This allows the customer to assess their capability.

MILESTONE: By 2000, develop a new service for VNA verification using kits in Type N and CPC-7 connectors.

Improvements in the measurement process for scattering parameter and impedance measurements as well as the dimensional characterization of transmission-line standards are necessary to decrease measurement costs. Alternative measurement techniques that do

"Our Customers insist on 'traceability' to a national standard for their measurements. This is one of the primary reasons we use NIST's services. We strive to meet this need by using calibration services offered by NIST to maintain in house standards which we use in the manufacture of our equipment."

Alden Bedard
Anritsu

not significantly reduce the measurement uncertainty are being explored.

MILESTONE: By 2000, perform experiments to determine the repeatability of measurements for transmission line length and relationship between airgauging and laser micrometer measurements of transmission line components.

MILESTONE: By 2001, complete the uncertainty analysis of 14 mm and 7 mm transmission line dimensional characterization. Complete documentation for the dimensional measurement of airlines.

MILESTONE: By 2001, automate the calibration of coaxial resistance standards using LCR meters and select calibrated standards and adaptors.

Accomplishments

- Evaluated a backward wave oscillator (BWO) to determine the suitability for use in the WR-15 dual six-port (50-75 GHz). The tests showed that satisfactory results could be obtained with the BWO oscillator. Adding a BWO oscillator to the dual six-port will give the system swept frequency capability, which should lower the calibration fees for measurement in this frequency band.
- Delivered an upgraded 0.25 to 18 GHz dual six-port vector network analyzer system to the Navy Primary Standards Laboratory in San Diego, CA. System design modifications improved the speed by a factor of four. The overall uncertainty of the system has also been reduced because of the improved RF signal treatment. The Navy will use the system to support their power and S-parameter measurement services with a more reliable and faster measurement system.
- Reduced the uncertainties for the 2.4 mm S-parameter measurement services. Based on analysis of check standard data it was determined that the Type A component for S_{11} and S_{22} could be reduced. The uncertainties for S_{11} and S_{22} have been reduced from 0.015 to 0.011 at 0.1 GHz and from 0.038 to 0.02 at 50 GHz.
- A new measurement service for verifying the performance of vector network analyzers has been initiated. The new service is based on NIST-owned traveling verification kits in which the customer measures one of NIST's verification kits and then sends the data back to NIST for analysis. NIST issues a formal report that compares the customer's measurements to those made by NIST. Included in the report are NIST's uncertainties, which a participant can incorporate into their analysis.
- NIST developed a dual six-port automatic network analyzer system for the Air Force Primary Standards Laboratory. This network analyzer operates from 18 to 40 GHz and uses wide band coaxial components and diode microwave power detectors.
- Calibrated 171 devices.

Fundamental Microwave Quantities

Noise

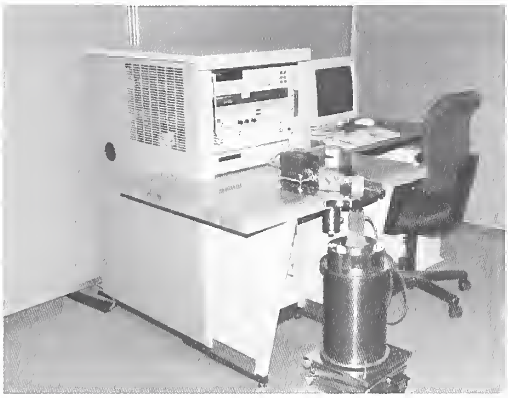
Technical Contact:
Jim Randa
Phone: 303-497-3150

Staff-Years:
2.75 professionals
2.5 technicians
0.25 guest scientists

Funding Sources:
NIST (60%)
Other (40%)

Project Goals

Develop methods for very accurate measurements of thermal noise; provide support for such measurements in the communications and electronics industries, as well as for other government agencies.



Noise figure radiometer and coaxial standard

Customer Needs

Noise is a crucial consideration in designing or assessing the performance of virtually any electronic device or system that involves detection or processing of a signal. This includes not just communications systems, such as cellular phones or home entertainment systems, but also systems with internal signal detection and processing, such as guidance and tracking systems or electronic test equipment. The global market for microwave and millimeter-wave devices in these areas is already huge and is undergoing explosive growth. Important trends that must be addressed include the utilization of higher frequencies, the growing importance of low-noise amplifiers, the demand for and lack of repeatable, traceable on-wafer noise measurement techniques, and the perpetual quest for faster, less expensive measurements. The two most important noise-related technical parameters for industry are the noise temperature of a one-port source and the noise figure of an amplifier.

Technical Strategy

In traditional (connectorized) noise temperature measurements and calibrations, the goal is to cover the frequency range from 1 to 75 GHz for waveguide sources, and 1 to 50 GHz in systems using coaxial connectors. Concurrently, staff is also attempting to reduce the time required for such calibrations, thereby reducing the costs.

MILESTONE: By 2000, develop WR-22 (33 to 50 GHz) noise-temperature measurement service; Extend 2.4 mm service up to 50 GHz; Construct and begin testing new coaxial radiometers (1–2, 2–4, 4–8, 12–18 GHz).

MILESTONE: By 2001, reopen coaxial noise services below 12 GHz.

The second general thrust of the project is for amplifier noise figure measurements, where the goal is to develop cost-effective measurement services for amplifiers with coaxial connectors over the frequency range 1 GHz to 18 GHz.

MILESTONE: By 2000, formalize noise-figure measurement techniques and write associated software; Analyze noise figure uncertainties; Offer a measurement or comparison service for amplifier noise figure for GPC-7, 8-12 GHz.

MILESTONE: By 2001, develop and open noise-figure service for other bands and/or connectors.

The third major effort is in developing on-wafer, noise measurement methods to characterize devices and amplifiers in integrated circuits. This will first be done for noise temperature and subsequently for amplifier noise figure.

MILESTONE: By 2000, fabricate and test improved on-wafer noise-temperature transfer standards; Initiate on-wafer noise-temperature round-robin comparison with industrial labs.

MILESTONE: By 2001, complete on-wafer noise-temperature round robin; Investigate on-wafer noise figure methods.

Central to all three of these efforts is the new noise-figure radiometer (NFRad) system which is currently under development. It has been designed to measure either one-port noise temperature or two-port amplifier noise figure, and it has the potential to be significantly faster than our existing radiometers.

"The on-wafer semiconductor device characterization is getting more and more important in the test and measurement world. Since new technologies now provide very low-noise devices, every improvement made in term of accuracy is crucial and will have a real impact."

Ali Boudiaf
ATN Microwave

MILESTONE: By 2000, construct and begin testing new coaxial radiometers (1–2, 2–4, 4–8, 12–18 GHz).

MILESTONE: By 2001,complete testing of new coaxial radiometers.

Accomplishments

- Completed the development of a new measurement service for noise temperature for 2.4 mm coaxial sources and opened the measurement service. The new service offers continuous coverage from 8 to 40 GHz, with the exception of two small gaps. It is capable of measuring sources with noise temperatures from about 50 K to 15,000 K. Typical expanded ($k = 2$) uncertainties are between 1 % and 1.4 % up to 26 GHz and between 1.5 % and 1.7 % from 26.5 to 40 GHz, for a source with a noise temperature of about 5000 K to 10,000 K.
- A comparison of three different methods for characterizing precision adapters was completed. Several adapters were characterized with each method, and the results agreed to within the estimated uncertainties that ranged from about 0.002 to 0.012, depending on the method, connector, and frequency. Two papers were written reporting the results: one was presented at the 1999 IEEE MTT-S International Microwave Symposium, and the other published in the IEEE Trans. on MTT.
- A set of measurements was performed and analyzed to test the stability of a noise source submitted by the Jet Propulsion Laboratory (JPL). By repeatedly measuring the noise temperature over the course of a week, we were able to measure the stability to within about 2 K (about 0.024%) per day, roughly 10 times better than we had "promised." This success led to stability measurements on other types of noise sources, for periods of about one week and about one year. Results will be presented at CPEM-2000 and in a paper submitted to the IEEE Transactions on Instrumentation and Measurement.
- The software for noise-temperature measurements on the new coaxial radiometer (NFRad) was completed and tested. The testing of the NFRad for 8 to 12 GHz was completed. Good results were obtained in all the tests, culminating in very good agreement with noise temperatures of devices previously measured on the old coaxial system. A NIST Technical Note summarizing the system design and test is in progress.
- A combined effort by the Microelectronics and Noise Projects resulted in the design, fabrication, measurement, and characterization of prototype on-wafer noise sources. They were fabricated by the Microelectronics Project, using on-wafer attenuator structures supplied by Cascade Microtech. Software was written for the data analysis, and measurements were made on the on-wafer noise sources. Some previous measurements of on-wafer noise temperature from off-wafer sources were repeated as a check. Good results were obtained. The sources exhibit approximately constant noise temperatures and acceptably small reflection coefficients (≤ 0.12) across the frequency range measured (8-12 GHz). Two papers were written reporting the work, a short paper presented at the ARFTG conference in June 1998, and a full-length paper published in IEEE Transactions on MTT.
- An international comparison of thermal noise measurements, (GTRF-92-2), was recently completed under the auspices of CIPM/CCEM, with NIST serving as the pilot laboratory. The noise temperatures of two solid-state noise sources with GPC-7 connectors were measured at 2, 4, and 12 GHz at the national measurement laboratories in France (BNM-LCIE), Germany (PTB), the United Kingdom (NPL), and the United States (NIST). Good agreement was found among the results from the different laboratories, with all results agreeing within the expanded uncertainties, which ranged from 0.5% to 2.9%. The comparison was performed in accordance with the guidelines recently adopted by the CCEM. A paper reporting the comparison was presented at the Conference on Precision Electromagnetic Measurements, held in Washington, DC, in July 1998, and a full report was published in the IEEE Trans. on Instrumentation and Measurement.

- The measurement service for the noise temperature of WR-15 waveguide noise sources for the frequency range 50 to 65 GHz was reopened. The service originally covered only 55 to 64.5 GHz, and problems led to its closure about five years ago. To recertify the system, critical system checks were performed, the six-port reflectometer software was improved, the uncertainty analysis was checked and updated, and check standards were remeasured and compared to previous results. Typical expanded uncertainties (2 sigma) for the revived service are expected to be about 1.9% for noise temperatures of 5000 K to about 12,000 K. The WR-15 band extends from 50 to 75 GHz. Principal applications in this band are cross links between and among satellites around 60 GHz.
- Calibrated 6 devices.

High-Speed Microelectronics

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Staff-Years:
3.0 professionals
1.0 technicians
0.1 guest scientists

Funding Sources:
NIST (80%)
Other (20%)

" I really appreciated the paper 'Forumulations of Basic Vector Network Analyser Error Model including Switch Term' by Dr. Roger Marks. It provided insights as to how I was correcting for the transfer switch. We at Anritsu greatly appreciate the work you both have done. Thank you for you contribtutions.

Gary Chock
Anritsu Company

Project Goals

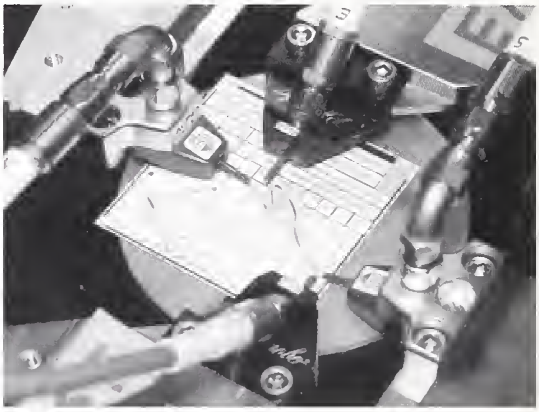
This project was formed in 1989 to address industry demands for metrology appropriate to monolithic microwave integrated circuits (MMICs), which have become increasingly prevalent in low-cost, low-power wireless communications systems. This demand led to the creation, with industry funding, of the NIST Industrial MMIC Consortium, which extended beyond its initial five-year lifetime. The increasing importance of electronic packaging in limiting the performance of digital and other circuitry has led us to expand the project to include high-speed microelectronics packaging and digital-interconnect characterization. This requires the development of new metrology for characterizing complex multiport systems, coupled lines, and lossy silicon interconnects.

High-speed microelectronics metrology supports these industries through research and development of on-wafer metrology, including the fabrication of coplanar and microstrip calibration standards, the development of measurement methods for scattering, impedance, and noise parameters, and the development of methods for the characterization of complex interconnect structures.

The project is supported by the NIST Industrial MMIC Consortium, which provides close collaboration with industry in developing accurate and traceable on-wafer measurements. The project aims for practical calibration and measurement methods that are suitable for commercial laboratories. Methods are implemented in instrument control and data processing software that interface with a range of laboratory instruments, including microwave network analyzers, radio-frequency network analyzers, and digital sampling oscilloscopes. This range of options brings the advanced NIST technology into the hands of microwave, wireless, and digital engineers

Customer Needs

The explosion of wireless applications is fueling the demand for microwave and radio-frequency microelectronics, and advances in the silicon industry continue to drive the size of digital circuits down and their clock rates up to microwave frequencies. These trends in the wireless and digital industries have led to increasingly stringent requirements for the electromagnetic characterization of monolithic microwave integrated circuits (MMICs), dense multilayer interconnects, and other high-speed microelectronic structures. In response to these requirements, NIST researchers are developing measurement methods to characterize key high-frequency components and high-performance electronic packages and interconnections.



Multi-port on-wafer measurements

Technical Strategy

The monolithic microwave circuit industry must reduce testing costs to maintain its global leadership position. To reduce testing costs the industry has adopted on-wafer testing techniques. NIST is developing metrology and software for on-wafer characterization, and verification procedures for establishing traceability paths.

MILESTONE: By 2000, improve the accuracy of Cascade's SOLR calibration. Develop calibration for membrane probes and compare it to standard industry calibrations. Work with statistical group to improve error analysis of TRL calibration. Assemble automated probe station and automate TRL measurements. Support the development and application of an on-wafer noise source. Compare effect of calibrations on device models with UC Berkeley.

MILESTONE: By 2001, work with industry to commercialize NIST's LRM calibration for imperfect standards. Extend device measurements to 100 GHz and apply 3-port device characterization schemes to transistor characterization with UC Berkeley. Develop compensation for via-hole differences, and other microstrip calibration errors.

MILESTONE: By 2002, extend multiport measurement capability to 50 GHz and apply to device characterization with UC Berkeley. Develop improved calibration methods that account for inherent differences in microstrip calibrations.

"Two programs developed by NIST, MultiCal™ and Cap™, enabled development of pre-matching networks with first-pass success, subsequently enabling my group to characterize transistors in a fashion which presently no other RF/MW company has."

John Sevic
UltraRF

Performance of many microwave and digital electronic systems is limited by the signal speed and signal integrity within the electronic packaging structures. In response to these limitations, NIST is developing measurement techniques for the characterization of electronic packaging.

MILESTONE: By 2000, integrate TRL calibration software and 4-port measurement software. Apply methods to characterize miniature cables, coupled lines on silicon, and conductor backed coplanar waveguide.

MILESTONE: By 2001, develop interface between 4-port measurement software and multiconductor transmission line analysis method. Develop accurate method for measuring low impedance levels found in power/ground plane problems. Develop methods for measuring low impedance levels found in power/ground plane problems with industry.

The transistors on high-speed digital integrated circuits are unable to drive the parasitic capacitance associated with conventional contact pads. NIST is working on developing calibration standards and measurement methods for noncontacting at-speed tests of digital integrated circuits.

MILESTONE: By 2000, develop calibration method for improved 10 GHz on-wafer sinusoidal voltage standard.

MILESTONE: By 2001, demonstrate digital on-wafer voltage standard in an at-speed test system. Design and construct a digital on-wafer standard and on-chip sampling system.

MILESTONE: By 2002, develop non-contacting probes and optical probing systems with Division 814. Compare performance of on-chip and conventional sampling systems.

Semiconductor manufacturers are using low-K copper interconnects to speed-up digital processors. However, there are no measurement methods available for measuring the dielectric properties of the thin-films. NIST is responding by developing procedures for characterizing low-K thin-films.

MILESTONE: By 2000, publish methods for thin-film characterization methods in microstrip lines developed in collaboration with SEMATECH. Fabricate and test standard structures for testing thin films with a US company.

MILESTONE: By 2001, collaborate with Materials Project to extend methods to characterize magnetic thin films. Collaborate on time-domain characterization of thin magnetic films.

Accomplishments

- Tested power monitors that will be part of a CMOS calibration chip with known voltages and currents. The chips will be used to calibrate instruments for an at-speed digital test. Sensitivity of power monitors is adequate for transferring voltages with 0.01V precision at 10 GHz.

- Developed a causal microwave circuit theory whose voltages and currents reproduce the temporal behavior of the actual electric and magnetic fields in the circuit. The new causal theory does this by linking the time and frequency domains. This fixes all of the remaining free parameters of conventional microwave circuit theory, resolving one of the most troublesome dilemmas of microwave circuit theory in a unique and creative fashion.

- Characterized low-K dielectrics fabricated at SEMATECH using transmission-line methods that were developed at NIST. Measurements from different line geometries agreed to within 5% up to 40 GHz. The work involved tight collaboration between NIST and SEMATECH. The test structures were designed at NIST, the samples were fabricated at SEMATECH, the electrical measurements and data analysis were performed at NIST, and the physical measurements and electromagnetic analysis were performed at SEMATECH.

- Developed a different approach to dielectric thin-film characterization at DOW Chemical, a major supplier of low-K dielectrics. In our collaboration with DOW, we micro-fabricate transmission lines at NIST; DOW simply deposits and patterns the thin films on pretested circuits provided by NIST. A second set of measurements made at NIST tests for the differences in transmission-line capacitance. NIST has completed fabrication of the test coupons, shipped them to Dow, and tested the first samples.

Wireless Systems

Technical Contact:
Don DeGroot
Phone: 303-497-7212

Staff-Years:
3.0 professionals
0.25 students

Funding Sources:
NIST (85%)
Other (15%)

Nonlinear Device Characterization

Project Goals

Develop new and general methods of characterizing nonlinear devices and components used in digital wireless communications, and transfer the methods to industrial research and development laboratories.

Measuring a PIM artifact

"Agilent Lightwave Division would like to encourage NIST's continued work to develop the nose-to-nose characterization, so that the technology can become more widely available."

Dennis Derickson,
Agilent Technologies

Customer Needs

Radio-frequency measurements are applied extensively in the deployment of commercial wireless communication systems. They are crucial to all stages of system development, from physics-based device modeling, to circuit design and system performance characterization. NIST's RF and microwave measurement support recently expanded to include methods of verifying nonlinear network models and measurements and methods for supporting industrial standards development.

Technical Strategy

The Nonlinear Device Characterization Project is focusing on the verification of model- and measurement-based descriptions of active devices and circuits containing nonlinear elements. Traditional microwave circuit design has relied on the ability to cascade circuit elements through simple linear operations and transformations. When a RF circuit includes a nonlinear element, engineers lose the ability to predict circuit performance across operating environments or states. With the wireless revolution, many researchers have devoted their time to developing models of nonlinear devices that will work with existing computer-aided design (CAD) techniques. Others have worked on developing specialized and functional tests that show how nonlinear behavior might effect system performance. Presently, there is a critical need for fundamental RF measurement techniques to develop and validate models and specialized tests. Contributions in this area will significantly improve design-cycle efficiency and compatibility between manufacturers.

The project's near-term goal is to establish a calibrated Nonlinear Network Measurement System (NNMS) at NIST with verifiable measurement uncertainty. The system will first be used to verify sample circuits developed at NIST and to predict functional test results based on the acquired waveform data. A custom instrument has been ordered and much research is under way to develop accurate calibration and measurement techniques for this system. Particularly, the Nonlinear Device Characterization Project is investigating the validity and measurement uncertainty of the Nose-to-Nose calibration, the only known method of measuring total phase delay of signals with bandwidth of 50 GHz.

***MILESTONE** By 2000, validate the Nose-to-Nose calibration. By 2001, verifiy the operation of a nonlinear network measurement system and implement advanced calibration methods.*

The Nonlinear Network Measurement System (NNMS) will be applied first to canonical active circuits to compare general measurements with predictions made by commercial CAD simulators. Secondly, the measurement system will be applied to verify artificial neural network (ANN) models for sample class-E amplifier circuits being developed in cooperation with the University

"Overall, I believe the [NIST] paper does an excellent job of outlining the [PIM] work ahead and summarizing the work to date. Implementing this more rigorous model is a significant step in understanding the behavior of PIM in cable assemblies."

Brad Deats
Summitek Instruments

"Our final goal is to develop the test structures, calibration procedures, and accurate measurements of S-parameters of Intel's MOSFETs. Collaboration between NIST and Intel will give some successful results for high frequency characterization of MOSFETs. This is very interesting."

David Cho
Intel

of Colorado. NNMS data will be used to train the ANN model, to verify circuit and model operation, and to validate a possible circuit optimization approach.

MILESTONE: By 2002, quantify uncertainty in commercial CAD simulator predictions for canonical circuits; develop and verify ANN models for example class-E amplifier circuits.

NIST is also conducting research into passive sources of nonlinearity found in wireless communications base stations. Key industry representatives have requested NIST's participation in passive intermodulation measurements. The Nonlinear Device Characterization Project responded by establishing relationships with a working group of the International Electrotechnical Commission that is developing PIM standards for connectors and cable assembly manufacturers. From this interaction, the project designed and conducted the first phase of a PIM measurement intercomparison. The study shows the level of agreement achieved by the participants, but does not show the impact of a given PIM level on system performance. The latter has become important in directing future NIST activities.

MILESTONE: By 2001, correlate PIM with system performance; conclude 2nd phase PIM intercomparison study.

Time-domain measurements form an interesting alternative to continuous wave nonlinear device measurements. Presently, NIST is investigating full vector correction of a time-domain network analyzer system. These time-domain methods have been applied to linear passive networks up to 20 GHz, but they can be extended to enable broadband instrumentation for the mm-wave region.

MILESTONE: By 2001, add multiline TRL calibrations to TDNACal; complete two-port error model.

Accomplishments

- In response to requests by U.S. industry and members of the International Electrotechnical Commission (IEC), members of the Nonlinear Device Characterization Project conducted the first phase of the Passive Intermodulation Measurement Intercomparison for the U.S. Wireless Industry. While the study shows reasonable standard deviations about the expected mean values for most of the data sets, it reveals significant discrepancies reported by some participants and large standard deviations in other cases. This study is already enabling these companies to improve their PIM measurement capabilities.
- Through a collaborative effort, members of the RF Electronics and RF Fields Groups provided US West with the means to measure passive intermodulation distortion in base-station antennas. This work made use of the new anechoic chamber and new measurement techniques under development at NIST. NIST provided support and advice to US West engineers throughout the measurements. In addition, the collaboration allowed NIST to conduct PIM measurement experiments for the development of a new de-embedding technique. US West found the data collected in the anechoic chamber to be superior to data collected from their previous open range measurements.
- Developed a complete Open-Short-Load-Thru (OSLT) calibration for the NIST TDNACal software that implements equivalent circuit model descriptions. This new calibration is a significant enhancement to TDNACal, and for the first time, allows NIST to study measurement uncertainty in OSLT calibrations that make use of the equivalent-circuit model parameters.
- Collaborated with the Intel Technical CAD (TCAD) Division to measure the behavior of high-speed digital transistors (that is, MOSFETs) and to extract accurate device parameters. After much effort and several inter-laboratory visits, the first phase of the project has culminated in great success. The key technological hurdles were the measurement of three-port devices when the three ports are connected in different metalization layers, and the high RF losses encountered in commercial CMOS technology. NIST personnel designed two sets of calibration standards for the three-port devices. Intel fabricated three generations of test wafers and worked with NIST in verifying the calibrations. This activity also relied on new software

developed by the High-Speed Microelectronics Project to remove contact-pad effects. The new approach is being used by TCAD engineers to quantify device behavior with a much higher degree of accuracy.

- Characterized the accuracy of several proposed calibration techniques for microwave vector network analyzers (VNAs). Project staff discovered significant errors in the proposed methods and introduced a new robust SOLT calibration method that offers demonstrably improved accuracy in four-sampler VNA measurements.

Wireless Systems

National Wireless Electronics Systems Testbed (N-WEST)

Technical Contact:
Roger Marks
Phone: 303-497-3037

Staff-Years:
1.0 professionals
1.0 guest scientists

Funding Sources:
NIST (100%)

Project Goals

The mission of the National Wireless Electronic Systems Testbed (N-WEST) is to promote the development of the broadband wireless communications industry by creating and carrying out tests and measurements and by promoting sound operational standards and specifications based on open technical results.

Customer Needs

With the start of U.S. auctions in 1994, the radio spectrum has been moving into private hands. This spectrum is nearly unregulated. Innovation has brought new technology to market, but without widely supported standards, costs remain unnecessarily high, exports are stifled, and the benefits of new technology fail to fully flow down to the consumer.

N-WEST intends to be a tool for NIST to take a proactive role in the development of technically superior standards for wireless communications. Its current focus is on fixed broadband wireless access systems, which have the potential to provide competitive alternative connections to Internet, voice, and video networks for residential and business sites. Spectrum for these services is in private hands, but the widescale deployment of systems awaits standardization.

Technical Strategy

Standardization Effort

The initial N-WEST effort has been directed toward establishing and leading a global industry effort in broadband wireless access standardization. The project began by launching a web site <http://nwest.nist.gov> and newsletter (currently with over 750 subscribers) in April 1998 and then seeking supporting companies (currently numbering over 75). Following a strategy session of ten people in July, N-WEST drew 45 people to a Kickoff Meeting in August 1998 in conjunction with the 1998 IEEE Radio and Wireless Conference, chaired by N-WEST founder Roger Marks. At the meeting, Marks suggested that the most appropriate organization with which to pursue standardization was the LAN/MAN [Local/Metropolitan Area Networks] Standards Committee of the Institute of Electrical and Electronics Engineers, Inc. (IEEE), a nonprofit technical professional society. The IEEE, through its accredited Standards Association, supports an open process for global standards development. The committee, informally known as IEEE 802, has become the world's primary (and virtually only) developer of standards for computer networking and its Ethernet standards are ubiquitous. At the August Kickoff Meeting, the participants endorsed the IEEE 802 approach, and the group met again in November 1998 under the N-WEST aegis during the IEEE 802 Plenary Session. At that session, IEEE 802 initiated the temporary IEEE 802 Study Group on Broadband Wireless Access, and Marks was named Chair.

IEEE 802.16 attendees meet during November 1999

The Study Group has met twice in its limited life, attracting 97 participants from over 70 companies during meetings in January and March 1999. In March, IEEE 802 created the standing IEEE 802.16 Committee on Broadband Wireless Access and named Marks as Interim Chair. He was later elected to a full term by unanimous vote of the membership.

IEEE 802.16 first met in Boulder in May 1999 and has since met in July, August, September, and November. The group has two approved projects: an air interface for systems in the 10-66 GHz range and a recommended practice on coexistence. A Study Group on an air interface for systems below 10 GHz was initiated in November 1999. The group has 106 Voting Members and 200 people from over 110 companies or institutions have attended at least one of the 3-5 day sessions. Marks' plan for the

development of the air interface standard was adopted by the group and began with the consideration of 32 proposed standards at the November 1999 meeting. Plans call for the coexistence specification to be complete in July 2000 and the first air interface standard to be ready in draft form during November 2000.

In accordance with IEEE 802 rules, Marks, as Working Group Chair, decides the Group's procedural issues while the Group makes the technical decisions. Marks also maintains the web site.

Testbed

The primary goal of the testbed is to support standardization by providing unbiased measurement results. As the standard takes shape, this may evolve into a role in compliance testing.

The testbed itself is still in the conceptual development stage. Two Guest Researchers visiting from January-June 2000 are expected to play a large role in its initial realization.

Electromagnetic Properties of Materials

Technical Contact:
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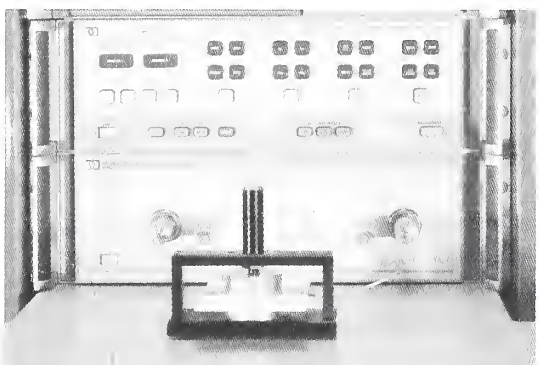
Phone: 303-497-5621

Staff-Years:
4.0 professionals
1.0 technicians
0.15 guest scientists

Funding Sources:
NIST (65%)
Other (35%)

Project Goals

Develop, improve, and analyze measurement methods and uncertainty estimates for characterizing the complex permittivity and permeability of dielectric and magnetic materials in the RF and microwave spectrum, as a function of temperature and bias fields. In addition, develop measurement methods for conductor surface resistance over the RF/microwave spectrum. Develop new nondestructive measurement techniques to support emerging technologies such as dielectric, ferroelectric, and ferromagnetic thin films. Develop models for underlying relaxation phenomena that occur in dielectric and magnetic materials. Provide measurement services and Standard Reference Materials (SRMs) to industry and others. Organize and implement measurement comparisons and interact with standards committees and workshops.



Measuring a PWB sample in the split cylinder resonator

Customer Needs

Bulk and thin-film electronic materials are widely used in industry for applications such as printed wiring boards (PWBs), substrates, electronic and microwave components, antenna lenses, and microwave absorbers. Thin films form the basis for microelectronic circuitry and substrate-based components. Dielectric properties of low-loss crystals are crucial in the wireless and time standards arena. There is a critical need to accurately characterize the dielectric and magnetic properties of newly developed ceramics and ferrites for the wireless industry. Computer-based design methods require very accurate data on the dielectric and magnetic properties of these materials over a wide frequency spectrum and temperature range. Much improved and new measurement methods with well-characterized uncertainties are needed. There is a particular need for small, nondestructive, dielectric resonators that can be used on-line to characterize test coupons or panels of low-temperature cofired ceramics (LTCC) in PWB manufacturing. Dielectric reference materials provide measurement traceability to NIST and intercomparisons provide assessments of the quality of material characterization.

Technical Strategy

In order to support the microelectronics industry it is important to understand their specific needs. We have identified a need for the characterization and development of accurate on-line and laboratory resonator techniques. We are developing improved resonator techniques and SRMs for medium-and low-loss bulk solids and substrates.

MILESTONE:* *In 2000, develop an improved theoretical model and software for the split-post resonator and update software into LABVIEW format for serveral resonator tecniques. Identify nondestructive resonator methods for development as process control methods. Attend LTCC nondestructive testing and IPC workshops and standards committees in this area of research.

To satisfy the need in the PWB and LTCC industries for accurate characterization of thin materials we are developing variable temperature metrology for characterizing ultra low-loss dielectrics, PWBs, and substrates.

MILESTONE:* *In 2000, measure an array of important low-loss crystals, polymers, and ceramics as a function of temperature and present journal paper summarizing the new measurements. Serve on IPC and ASTM standards committees.

The microelectronics industry needs accurate characterization of thin-films. Therefore, we are developing new transmission-line and resonator metrology for characterizing thin substrates and thin films.

MILESTONE:* *In 2000, continue measurements of both patterned and unpatterned dielectric thin films using resonator methods. Evaluate new methods for process-control applications.

There is an increasing need to develop accurate methods for measuring frequency-agile materials. These materials are needed in new phased-array antennas and other components. Therefore we are

developing improved and new techniques for characterizing bulk and thin-film ferroelectrics.

MILESTONE: By 2000, complete above measurements on bulk ferroelectrics. In collaboration with the Army Research Lab, begin measurements of unpatterned ferroelectric thin films using resonator techniques. Develop a theory for ferroelectric relaxation. Develop a dielectric resonator technique for measuring ferroelectric thin films.

In the biotech industry there is increasing emphasis on utilizing dielectric methods for modeling biochips and bio-tissue response. Therefore we are developing fluid characterization techniques.

MILESTONE: By 2000, upgrade software for coaxial probe and shielded open-circuited holder techniques. Compare measurement methods on liquids with dfferent fixtures.

In order to keep abreast of the current physics of dielectrics we are studying the underlying relaxation models for dielectric and magnetic response.

MILESTONE: By 2000, study magnetic relaxation using statistical-mechanical models. Investigate percolation models of dielectric mixtures.

Accomplishments

- Developed a new full-mode model for the split dielectric cavity that is critical to the development of nondestructive testing methods for dielectrics. This model greatly increases the accuracy of the measurement technique. Previous models are single mode and use a gap correction technique. The new model will be useful for characterization of thin materials used as substrates and PWBs. During this work there have been collaborations with Dielectric Labs Inc.
- Developed new transmission-line metrology, jointly with the High-Speed Microelectronics Project, for characterizing thin substrates and thin films. We have completed initial electrical testing of microstrip/coplanar waveguide test structures designed and fabricated at NIST. Test structures were returned to Dow for deposition of low-K dielectric thin films. We will complete final electrical testing after the second round of test structure fabrication is finished.
- Published Technical Note 1512 on printed-wiring board measurement metrology. This Note summarizes and compares the different techniques that can be used to measure PWBs and presents a large number of measurements on substrate materials. This Note has been given a number of positive reviews in technical journals and we have received approximately 50 requests for this document.
- Rogers Corporation, a leading supplier of microwave substrates and printed wiring boards recently collaborated with NIST to accurately measure the dielectric properties of one of their composite materials (RO3003) that consist of randomly oriented ceramic particles in a polymer filler. In particular, the manufacturer needed measurements performed in the millimeter wave frequency range to meet the needs of electronic designers working at these frequencies. The measurement approach chosen also provided an additional benefit of being able to demonstrate that the material is weakly anisotropic. Previously, Rogers Corp. had attempted to obtain such data at millimeter wavelengths from both industrial and academic testing laboratories, but the results proved inaccurate and inconclusive. This work is a typical example of NIST-industry collaboration wherein NIST performed very specialized material characterization measurements that the manufacturer was unable to perform independently. By making full use of NIST measurement capabilities and expertise, Rogers Corp. can reliably and accurately characterize their particular material in the frequency range desired.
- Developed jointly with the NIST-Boulder shops, the capability to machine polymer plastics. The capability has involved precision machining of cylindrically shaped specimens of relatively soft polymer plastics having low permittivity values in the range from 2 to 4. The dielectric properties of these were subsequently measured in the NIST 60 mm cylindrical cavity at 10 GHz and serve as national dielectric standards that are used to provide traceability in dielectric measurements from industry to NIST.
- In collaboration with a guest researcher, developed a unique capability to measure the RF tunability, $\Delta f/f$, versus applied voltage bias, where Δf is the change in frequency with applied voltage bias, in ferroelectric-composite thick films (approximately 0.25 mm thick). Previously such measurements

"On behalf of GE Plastics and the GE Corporate Research and Development (CRD) Center, I would like to thank you for providing an invaluable service in the dielectric characterization of our printed circuit board materials and plastics. The two techniques that you recommended (split-post resonator and reentrant cavity method) were implemented at GE CRD and have given us a highly accurate method of characterizing a wide variety of GE materials ..."

Vikram Krishnamurthy
GE Corporate Research and Development Center

could be performed only at low frequencies (approximately 1 kHz) using a capacitive fixture. These measurements were performed at VHF frequencies of approximately 100 MHz by use of a specially modified coaxial re-entrant cavity in which a voltage bias of up to 4 volts/μm can be applied across the sample located in the gap between the center conductors of the cavity. Preliminary measurement data obtained on a number of samples of differing compositions show that the tunability data versus applied bias at RF frequencies are essentially identical to those obtained at low frequencies. The data also show that there exists a linear region at bias values greater than 0.1volt per micrometer. Such information is of critical importance because it will allow designers to use the existing large body of low frequency tunability data that are available on these materials. Whether or not the RF losses also change with applied bias in the same manner as that seen at low frequencies remains a critical question. Our cavity fixture is currently undergoing further characterization in order to allow for accurate RF loss measurements during applied bias.

- Software for the SRM characterization was ported to the LABVIEW/C platform.
- The paper "Full-Wave Analysis of a Split-Cylinder Resonator for Nondestructive Permittivity Measurements" was published. Developed a Windows-based FORTRAN code incorporating new mode-matching split-cylinder theory. Software was distributed to an industrial lab for further evaluation.
- Carried out extensive collaboration with the Ceramic and Polymer Divisions of the NIST Materials Science and Engineering Laboratory, on new electronic material development.

Antennas and Antenna Systems

Antenna Measurement Theory and Application

Technical Contact:
Andrew G. Repjar
Phone: 303-497-5703

Staff-Years:
3.0 professionals
1.0 technician

Funding Sources:
NIST (69%)
Other (31%)

Project Goals

To develop, refine, and extend measurement techniques to better meet current requirements and to anticipate future needs for accurate antenna characterization.

Customer Needs

- Microwave hardware continues to become more sophisticated over the years and NIST, by congressional mandate, is tasked with providing correspondingly sophisticated measurement support. Current demands include:
- Better accuracy. High performance systems, especially those that are satellite based, require maintenance of tighter tolerances.
- Higher frequencies. Millimeter wave applications up to 500 GHz have been proposed. NIST routinely receives requests for measurements above 75 GHz (near the current limit of support.)
- Low sidelobe antennas. Military and commercial communications applications increasingly require sidelobe levels 50 dB below peak, or better, a range where measurement by standard techniques is difficult.
- Complex phased-array antennas. Large, often electronically steerable phased arrays require special diagnostic tests to ensure full functionality.
- In situ measurements. Many systems cannot be transported easily to a measurement laboratory. Robust techniques are needed for on-site testing.
- Production-line evaluation and threat assessment. Techniques are required that emphasize speed and economy, possibly at the expense of the ultimate in accuracy.
- Evaluation of anechoic chambers and compact ranges. A number of widely used measurement systems rely on establishing a well characterized test field. Near-field methods can be used to evaluate and analyze the quality of these test fields.

Technical Strategy

NIST must expand the covered frequency range for antenna calibrations to meet the demands of government and industry.

MILESTONE: By 2001, upgrade services to include the band 75 to 110 GHz. By 2002, upgrade services to include the band 110 to 170 GHz and develop metrology for the band 170 to 260 GHz.

To ensure accuracy, it is necessary to determine the quality of the incident field in the quiet zone of compact near-field or far-field ranges and anechoic chambers.

MILESTONE: By 2000, complete quiet-zone evaluation software. This software will produce an image of the measurement facility to aid in the identification of unwanted signal sources. Do sample measurements and introduce sources of non-ideal fields and verify that they can be detected.

Measurements, especially at millimeter-wave frequencies, often require probe-positioning tolerances that are difficult to maintain. The position of the probe can be accurately tracked with a laser interferometer. This tracking information can be used efficiently to correct measurement results for probe-position errors.

MILESTONE: By 2001, adapt probe position-correction software (that has been completed for planar near-field scanning) for application to spherical and cylindrical near-field scanning.

One of the larger sources of error in near-field measurements is multiple interactions between the probe and the test antenna. Although this effect is included in the general theory, there currently is no practical compensation method.

MILESTONE: By 2001, complete a study on compensation for multiple interaction errors, possibly involving a simplified scattering model for electrically small probes.

In planar near-field scanning, measurements are required over an infinite plane. Practically, the necessity of truncation leads to errors in pattern prediction that can be especially serious for broad-beam antennas. There are several methods that have potential to reduce truncation errors.

MILESTONE: By 2002, complete a study on the reduction of truncation errors using maximum entropy methods and/ or prolate spheroidal function representations.

The near-field extrapolation method, developed at NIST, is one of the more accurate ways of characterizing the on-axis gain and polarization properties of antennas. Further improvement is possible, however.

MILESTONE: By 2002, extend the extrapolation software to take full advantage of phase information and to analyze the conditioning of the algorithm.

Accomplishments

- Two Ku-band probes for the quiet-zone measurements have been designed and built. The probe arm support structure has been fabricated, and the receiving characteristics of the probes have been measured.

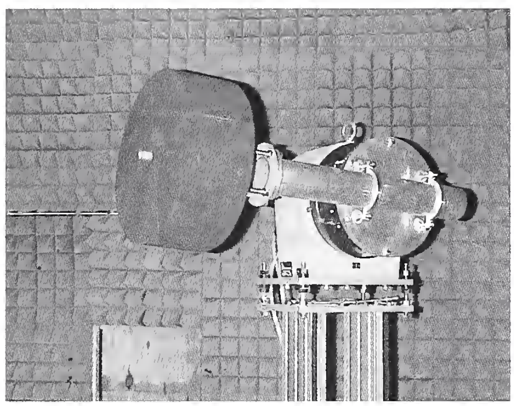
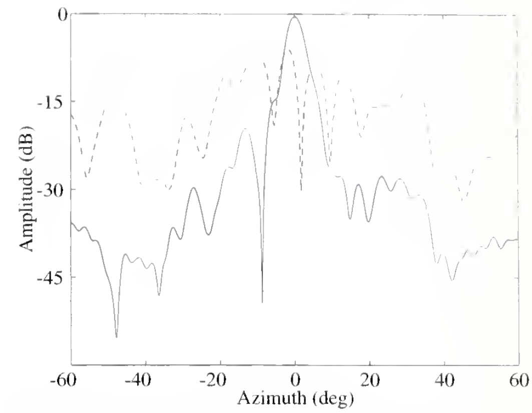


Figure showing the setup for a quiet-zone scan. In an actual measurement the exposed metal on the rotator and tower would be covered with microwave absorber. The probe is just visible in the left center, slightly beyond the end of the absorber.

- Preliminary quiet-zone measurement data have been acquired. Initial results are promising since the effects of an improvised scattering source (a ladder) intentionally placed in the range are visible.
- A 3D, probe position-error correction scheme has been worked out and published for planar near-field scanning applications. Software is available to the public.
- NIST offers annually, with the Georgia Institute of Technology, an introductory course on antenna measurements. Every other year NIST presents an in-depth technical course restricted to near-field methods pioneered at NIST.
- Software is currently available for planar, cylindrical, and spherical scanning applications. Probe position-correction software is available for the planar methods. Quiet-zone evaluation and imaging programs are expected by 2001.



This figure shows an antenna pattern (bottom curve) and the result of a simulated measurement (top curve) where random probe position errors on the order of a wavelength have been introduced. NIST software permits accurate, efficient recovery of the original pattern. The corrected result is not distinguishable from the original at the scale of the plot.

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Antennas and Antenna Systems

Metrology for Antenna, Wireless, and Space Systems

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Michael H. Francis
Phone: 303-497-5873

Staff-Years:
2.0 professionals
1.0 technician

Funding Sources:
NIST (50%)
Other (50%)

Project Goals

To maintain and develop the standards, methods, and instrumentation for measuring critical performance parameters for earth terminals, satellites, and other critical antenna systems such as those associated with public safety.

Customer Needs

Satellite communication is a high-precision technology requiring accurate measurements of antenna gain, noise temperature, G/T (system gain divided by system temperature), and EIRP (effective isotropic radiated power) to ensure optimum performance. Ground metrology stations and test ranges needed to monitor performance of commercial and government satellites require traceability to NIST standards. Measured satellite performance is used to determine incentive-clause payments to satellite contractors or charges billed to users or lessees. It is necessary that the results produced at these facilities be of the highest accuracy. New capabilities are needed to support emerging technologies such as anticollision radars. NIST traceability is also required by law enforcement agencies to ensure the accuracy of their speed measurement devices, down-the-road radar, across-the-road radar, and lidar.

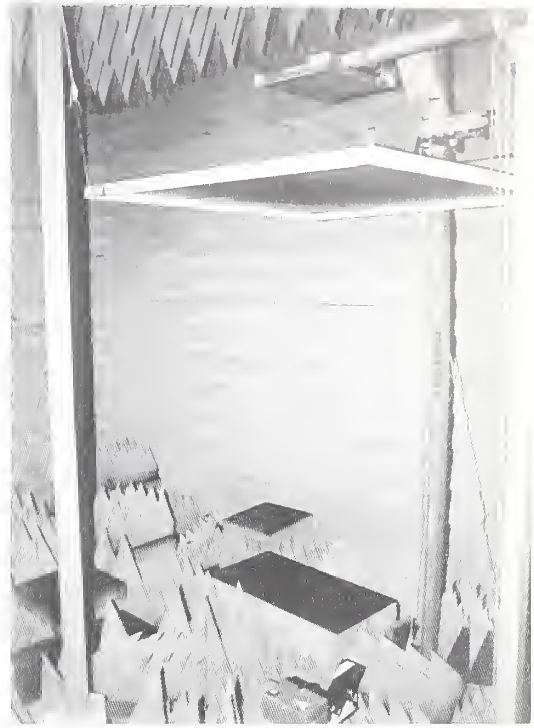
Technical Strategy

NIST currently maintains measurement standards and capabilities for frequencies from 1.5-75 GHz. Automobile anticollision radar will operate at frequencies of 76-77 GHz and aircraft anticollision radar will operate at frequencies of 94-96 GHz.

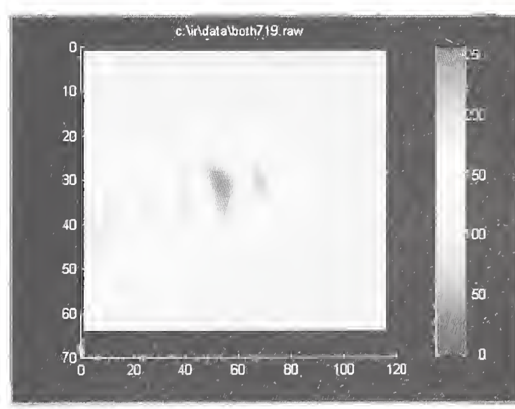
***MILESTONES:** By 2000, define anticollision radar system testing requirements and evaluate existing metrology for system parameter measurements.*

***MILESTONES:** By 2001, develop metrology and artifact standards for automobile anticollision radars.*

***MILESTONES:** By 2002, develop metrology and artifact standards for aircraft anticollision radars.*



Set-up for thermal imaging holography measurements. The large rectangular object is the resistive screen; the test antenna is in the upper center, the reference horn in the upper right, and the infrared camera is in the lower center of the picture.



Thermal image of the near-field interference pattern of a microstrip antenna and standard gain horn.

Antenna systems are often tested in indoor laboratory environments. The outdoor environment in which they operate has additional sources of noise that change the system noise and add to the system noise temperature. To accurately predict the performance of antenna

systems in the operating environment from their performance in the laboratory, it is necessary to be able to predict the noise due to sources of noise in the operating environment.

MILESTONE: By 2000, determine the G/T of an antenna both indoors and outdoors and evaluate the ability to predict outdoor performance from indoor measurement.

Large antenna systems cannot be evaluated in an indoor laboratory environment. A method is needed to evaluate large antenna systems in situ.

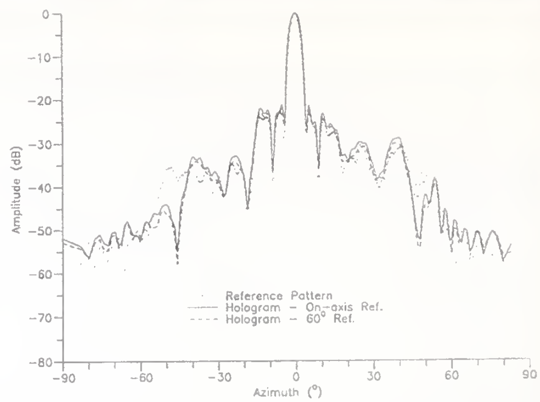
MILESTONE: By 2001, develop thermal holographic methods for large antenna system diagnostics.

To ensure the accuracy of police measurement devices, the International Association of Chiefs of Police (IACP) must have adequate test equipment.

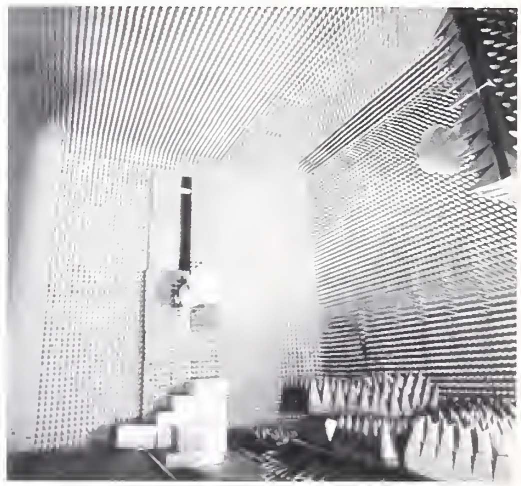
MILESTONE: By 2000, provide a working lidar speed-simulator system to be used at an IACP laboratory to be established at the University of North Florida. By 2001, develop and provide a working across-the-road radar speed simulator.

Accomplishments

- Developed the theory of using infrared/microwave holography for transmitting antenna measurements in collaboration with the University of Colorado, Colorado Springs (UCCS). As part of this effort, NIST performed tests and analyses on a small 4 x 4-element array and a 1.2-m dish operating at 4 GHz.
- Established program to provide support for the International Association of Chiefs of Police (IACP) testing program for traffic speed-measurement devices including down-the-road radar, across-the-road radar, and lidar.
- Designed an across-the-road radar speed simulator for use in IACP test laboratories.
- Evaluated software developed under a Small Business Innovative Research grant that predicts outdoor antenna system performance from indoor measurements.
- Mike Francis was elected present President of the Antenna Measurement Techniques Association (AMTA) for the year 2000. AMTA is an international organization with a membership of about 400 scientists and engineers.



Comparison of the far field as determined by conventional near-field methods (dotted line) and from thermaly imaged holograms (dashed and solid lines).



The NIST probe pattern range with the fixed probe located near the center of the photo and the moving probe located on the moving tower in the upper right of the photo.

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Antennas and Antenna Systems

Radar Cross Section

Technical Contact:
Lorant A. Muth
Phone: 303-497-3603

Staff-Years:
2.0 professionals

Funding Sources:
NIST (10%)
Other (90%)

"It is widely recognized that our national measurement capability needs to be strengthened and improved. I wholly support the goals of the RCS Range Certification Project that will establish sustainable and reasonable quality standards and practices for all ranges supporting our nation's investments in low observable technology. It pleases me greatly to see our organizations cooperating so well on these important topics..."

Richard Paul
Major General, USAF
Commander, AFRI, WPAFB

Project Goals

To create and implement a national quality assurance program for radar cross section (RCS) measurement ranges to ensure high quality RCS calibrations and measurements with stated uncertainties.

Customer Needs

RCS measurements on complex targets, such as aircraft, ships, and missiles are made at different types of RCS measurement ranges. For example, a compact range (indoor static), an outdoor static, or an outdoor dynamic facility. Measurements taken at various ranges on the same targets must agree with each other within stated uncertainties to increase confidence in RCS measurements industry wide. Although the sources of uncertainty are well known, a comprehensive determination of the magnitudes of uncertainties in RCS calibrations and measurements has yet to be accomplished at any of the government or industrial ranges. Such studies are essential at every RCS measurement range, if the US RCS industry is to maintain its world leadership well into the next millenium. To satisfy this requirement we need to establish well formulated procedures that measurement ranges can use to determine their uncertainties.

Technical Strategy

The complex measurement systems and measurement practices at RCS ranges need to be uniform throughout industry to enable meaningful comparisons of capabilities and important characterizations of range-to-range differences. The framework of an RCS Range Book, in the context of an RCS Certification Program, has been recommended to ensure community wide compliance. A DoD Demonstration Project is in progress to assess the feasibility and usefulness of such a program. A thorough technical analysis of the currently followed measurement procedures is essential to reveal areas of strength and weaknesses and to foster appropriate improvements.

The standard cylinder set adopted by the RCS community for calibration of RCS measurement systems will be evaluated, characterized, and refined as the most likely candidate for the NIST Standard Reference Material program. The results of interlaboratory comparison programs using these cylinders would be more reliable if we had specification data on all the cylinders used by the various ranges. We expect to manufacture a cylinder set for in-house use in the near future.

The basic cylinder set used to calibrate static RCS measurement systems in the frequency range of 2-18 GHz. The cylinders are made of aluminum, and are manufactured to a tolerance of ±0.0127 cm.

To calibrate a RCS measurement system we need to know the computed RCS values of the calibration artifacts. We are planning to implement a computational effort to determine the cross section of calibration artifacts with known uncertainties. After a national review of the computational procedures and results, we will recommend that such data be adopted for Standard Reference Datasets.

The following research areas in RCS measurement technology will advance the state of RCS measurements:

- A set of standard calibration artifacts to be used by industry to assess and improve calibration accuracy.
- Rigorous uncertainty analyses for all RCS ranges.
- A RCS interlaboratory comparison program and the corresponding technology to establish confidence in the uncertainty analyses, in the calibration of RCS artifacts and, in the measurements on unknown targets.

MILESTONE: By 2002, conclude the RCS Range Book reviews for industry, and publish a report summarizing NIST's observations as to the usefulness and feasibility of the certification process; make appropriate recommendations for improvements. Continue the research and development as defined in FY 2001. Make

recommendations for further improvements to RCS calibration measurement procedures.

MILESTONE: By 2001, continue the RCS Range Book reviews as required by industry. In addition, work closely with a selected RCS range to develop detailed procedures to determine RCS calibration and measurement uncertainty. Develop and publish an uncertainty analysis both for monostatic and bistatic RCS measurements at the selected facility. Develop an expanded set of RCS calibration artifacts to be able to calibrate the system at various signal levels of interest, and conduct an interlaboratory comparison study to assess the results. Develop RCS calibration procedures in the Ultra-Wide Band Time Domain Reflectivity Laboratory here at NIST, and demonstrate fully the uncertainty procedures needed to assign uncertainties to RCS measurements.

MILESTONE: By 2000, conduct RCS Range Book reviews for the DoD Demonstration Project in support of the National RCS Range Certification Program. Provide in-depth comments to improve on the procedures used at the RCS measurement ranges. Fully assess the technical merit and deficiencies of existing calibration and measurement procedures, data analysis techniques and uncertainty analysis. Publish recommendations for improvements in measurement procedures. Further explore known problems in areas of dynamic sphere calibration, polarimetric calibration, etc. Organize the Fourth RCS Certification Meeting at NIST, Boulder to provide a forum for the RCS community to discuss procedural and technical issues.

Accomplishments

- We have reviewed 6 major government RCS measurement ranges during the first 2 years of the project. RCS-range personnel gave presentations to NIST staff in Boulder over a period of 3 days. Each presenter discussed their calibration and measurement, instrumentation, documentation, and uncertainty analysis procedures. A preliminary uncertainty analysis was performed jointly by NIST and the personnel of each RCS measurement range.

- We have published a general framework for RCS uncertainty analysis (NISTIR 5019) to stimulate interest in RCS uncertainty analysis at RCS measurement ranges. The work was disseminated to the RCS community at conferences and via direct communication. We have collaborated with personnel of the Naval Air Warfare Center, Aircraft Division, Patuxent River, MD to examine in-depth the uncertainties in dynamic sphere calibrations. As a result the uncertainties on dynamic ranges are much better understood, but more work is needed for a complete analysis. The results of this study were published in a NISTIR.

- We have collaborated with personnel of the Naval Command, Control and Ocean Surveillance Center, San Diego, CA to examine in-depth the uncertainties in dynamic naval ship measurements. The preliminary uncertainty analysis for this range has been published in a NISTIR (see Publications). Several improvements in the calibration procedures have been recommended and adopted as a result of this study.

- We have noted several areas for improvement in the dynamic sphere calibration procedures. The calibration data exhibited unexplained large variations and contained frequency components that indicated significant electromagnetic interference from unknown sources. Minor modifications to the instrumentation removed the unwanted frequencies, but large variations in the amplitude of calibration data remained. This lead to the recognition of the need to examine possible pointing problems in the radar tracking system. This research is still ongoing today.

- The RCS ranges reported less than satisfactory results with existing polarimetric calibration procedures. We developed a more robust calibration procedure wherein full polarimetric data is obtained using a dihedral rotating around the line-of-sight to the radar. The new procedure allows one to improve the signal-to-noise ratio, and check for alignment problems by exploiting the symmetry properties of the dihedral. Diffraction effects can also be minimized by properly shaping the edges and sides of the dihedral. Presence of unwanted spatial harmonics can indicate problems with the radar. A full uncertainty analysis still needs to be developed for this procedure. We are working with several of the RCS ranges to further study this technique.

- A basic cylinder calibration set (see figure) has been adopted by the RCS community to test the calibration integrity of monostatic RCS systems. Computed radar cross sections for the cylinder set have been obtained. These 4 cylinders have been measured at a number of government and industrial measurement ranges. We have consistently found that measurements agreed with the theoretical RCS to less than .5 dB. We have shown that such comparisons demonstrate good repeatability; however, the measurement uncertainties need to be determined by more robust independent procedures. The DoD Demonstration Project has been established to explore the feasibility and cost of a national RCS certification program. Three DoD measurement facilities

have undertaken to develop their RCS Range Books, which contain the full documentation of range procedures, as outlined in the ANSI Z-540 standards document. These Range Books will be submitted to an RCS Certification Review Committee for examination and comments. Two Review Committees have been established, and the Pax River Range Book has been submitted for review. We expect that all 3 Range Books will be reviewed by July 2000.

- We have organized RCS Certification Meetings annually for the last 3 years. A fourth meeting is currently being organized, to be held in March 2000. The purpose of these meetings is to discuss procedural and technical criteria for a national RCS certification program, to discuss known technical issues in RCS calibration and measurements, and to discuss progress on the DoD Demonstration Project. On the average, 60 representatives of government and industrial ranges have attended these meetings. Last year we also had 6 foreign nationals from the UK and Canada. Feedback has been consistently positive.
- We have adapted the ANSI Z540 standards document for use by RCS ranges. A Handbook for the Assurance of Radar Cross Section Measurements has been written to assist the RCS community to construct their Range Books. The Handbook is under review by NCSL; it is also being revised to reflect recent procedural changes in the certification process.
- Involved in the following collaborations:
  - RCS uncertainty analysis: Pax River and NRaD Naval facilities, and the RCS community Range Books: Air Force Research Laboratory, WPAFB
  - Polarimetric research: Eglin AFB
  - RCS uncertainty workshop: The Boeing Company, Seattle, WA
  - Certification meetings: RCS community.
  - RCS Range characterization: China Lake, CA
  - Standards Committee Participation
  - IEEE RCS Standards Committee.

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R. C. Wittmann, M. H. Francis, L. A. Muth, and R. L. Lewis, "Proposed analysis of RCS measurement uncertainty," Proc. Antenna Meas. Tech. Assoc., Long Beach, CA, pp. 51 - 57, 3 - 7 Oct. 1994.

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Electromagnetic Compatibility

Standard Electromagnetic Fields

Technical Contact:
Dennis G. Camell
Phone: 303-497-3214

Staff-Years:
2.5 professionals
0.5 technician

Funding Sources:
NIST (70%)
Other (30%)

Project Goals

To develop methods and techniques for establishing continuous wave electromagnetic (EM) reference fields to 100 GHz. To maintain this capability in support of U.S. industry, through traceability and international compatibility of antenna standards.

Customer Needs

Well-defined EM reference fields are necessary for antenna calibrations, antenna research and development, evaluation of EM field probes, and EM interference measurements. Standards requirements need references to establish traceability and international compatibility. Industry requires a NIST-traceable EM field measurement capability to reduce barriers to world-wide acceptance of U.S. products and practices, based on the principles of one product, one technically valid international standard, one conformity assessment (1998 MSL Strategic Plan).

Technical Strategy

As instrumentation and electronics in general achieve higher clock speeds, measurements are needed at higher frequencies. Techniques based on the lower frequencies can be used to create standard EM fields at these higher frequencies. NIST will extend current facilities for these measurements.

MILESTONE:* *By 2000, extend sensor and antenna calibration capabilities to frequencies above 50 GHz.

OATS (open area test site) facilities are accepted, worldwide, as standard sites for EMC emissions measurements. However, increased ambient signal levels are causing complications in repeatability and accuracy of measurements. New techniques are needed to help industry combat these problems.

MILESTONE: By 2002, develop robust methods for OATS calibrations in high ambient field environment.

Antennas under test at NIST OATS facility

Comparison of EMC emissions measurements at various industrial sites shows large variations. Development of a service to quantify the output from various reference emitters will address variations within U.S. industrial sites. Leadership and guidance from NIST is sought from industry.

MILESTONE: By 2001, develop RF emissions measurement service for 30 to 1000 MHz. This includes design and evaluation of measurement methodology including uncertainty analysis.

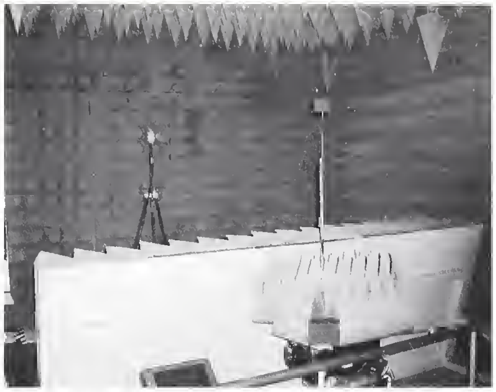
Anechoic chamber facilities are accepted as standard sites for free space measurements. Different methods, equipment, and even corporate philosophy cause variation in measurement results and uncertainties. NIST will theoretically and experimentally characterize these variations to improve harmony within the U.S. industrial community and elsewhere.

MILESTONE: By 2001, develop improved technique for characterizing anechoic chambers to establish uncertainty bounds for EM field measurements.

MILESTONE: By 2002, compare results and resolve discrepancies between standard site method and standard antenna method.

"Liberty Labs calibrates various antennas. Their customers ... need consistent data to produce high quality products. This consistency is obtained through traceability to NIST ... Liberty Labs has performed intercomparison measurements with other testing labs... and the NIST open area test site at Boulder, CO. These antenna calibrations and site intercomparisons allow Liberty Labs to be globally competitive in today's rf emissions testing community..."

Michael Howard
President
Liberty Labs
Kimballton, Iowa



Antenna measurements in NIST anechoic chamber

Accomplishments

- Testing in the newly refurbished NIST OATS decreased the expanded uncertainty for the standard antenna method from ±1.0 dB to ±0.8 dB. Improvements in the OATS included a solid-sheet steel center, conductive and weatherproof caulking of joints, and serrated edging for better edge transition.
- Method of moments modeling resulted in accurate calculations for the effective length and input impedance for the NIST standard dipoles. An error analysis was completed for the uncertainty assessment.
- A detailed analysis of uncertainties for the standard antenna method on an OATS was disseminated to industry, other government agencies, and standards organizations. Members of the EMC industrial community can apply the methodology to achieve their uncertainty values.
- Another method for evaluating anechoic chambers was developed in collaboration with CNET of France. It is called the pencil matrix method and involves the use of ray theory to predict reflections off anechoic chamber walls.
- Measurement of dual-polarized log-periodic antennas for the Federal Bureau of Investigation was completed.
- Participated in the annual IEC CISPR standards meetings and initiated a proactive level of technical support for the US delegates.
- This year's involvement with ANSI working group 1-15.6 on 'Geometry Specific Antenna Factors' provided technical insights that led to collaborations with industrial representatives for corrections to current ANSI Standard C63.4.
- Ten special tests were performed on probes/antennas for seven companies and government agencies.
- As part of the RF emissions calibration development, two collaborations were initiated to measure available reference RF emitters. One is with Hewlett-Packard and the other with USCEL (the U.S. Council of Electromagnetic Laboratories). Each arrangement will allow data sets from our partner to be compared to those from NIST.

Publications

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Electromagnetic Compatibility

Field Transfer Probe Standards

Technical Contact:
Keith D. Masterson
Phone: 303-497-3756

Staff-Years:
1.5 professionals
0.5 technician

Funding Sources:
NIST (50%)
Other (50%)

Project Goals

To provide electromagnetic field transfer probes with calibration traceable to NIST for various U.S. industries, including private test laboratories, and for other governmental agencies. Due to the wide range of applications, probes with different sensitivities and frequency responses are required. Projections for future spectrum usage indicate that probes with millimeter wave and terahertz responses will be needed, and their development is necessary.

Customer Needs

Many U.S. industries, including electronics, communications, law enforcement, aircraft, and automotive require accurate quantitative knowledge of the intensity of electromagnetic fields in test chambers, on open area test sites, or produced by various high power sources. The fields may be those generated as standards that are used to calibrate antennas and test hardware for susceptibility to electromagnetic interference, or those generated by the electromagnetic emissions from various electronic devices. Although most present applications cover frequencies from about 1 MHz to 10 GHz, there are collision-avoidance systems being developed by the automotive industry to operate at nearly 100 GHz, and future applications with much higher frequencies are envisioned for commercial applications.

Technical Strategy

NIST maintains somewhat parallel efforts to generate standard reference fields and to develop the probes required for their accurate measurements. The two efforts go hand in hand and are necessary to cross check against the uncertainties inherent in each effort.
NIST also cooperates with the national measurement laboratories of our international trading partners to perform round-robin testing and intercomparison of various standard antennas and probes to assure international agreement for their performance and further reduce uncertainties in areas that affect international trade. The probes we develop for this use also serve as the transfer standards needed by industry and other governmental agencies. Standard probes are designed so that response can be calculated from first principles, if possible, and for minimizing errors that occur from pickup of unwanted signals. For instance, at frequencies below about 5 GHz, the voltage generated across a tuned half-wave dipole can be calculated quite accurately and monitored via a DC signal on a resistive line. However, this approach is subject to errors introduced by the pickup of ambient electromagnetic fields by the dipole elements. Probes that maintain phase and amplitude information are needed for pulsed signal applications. If electrically coupled to readout instruments, they are subject to errors caused by pickup of signals in the lead wires. In addition to pioneering probe designs which are in current use, such as electrically coupled RF dipoles and resistively tapered dipoles, NIST has applied photonic technologies to electromagnetic field probes. Building on this expertise, we are pursuing programs in the following areas:

With commercial applications at millimeter wave frequencies already under development, the need for standard millimeter wave probes increases. Our current probes are able to only enter the low-frequency end of this regime. Losses and uncertainties associated with electrically connected probes become unacceptable. Photonic technologies, where the signals are transmitted along an optical fiber, hold a clear advantage. We will explore ways to utilize these advantages to fabricate and test probes with frequency responses above 100 GHz. Techniques that offer possibilities to extend the response to still higher frequencies will be favored. Thermo-optic probes already explored and reported upon by NIST will be reviewed in this context.

MILESTONE: By 2002, demonstrate a probe with frequency response of 100 GHz which also has the potential to become a transfer standard.

"H-P is currently working ... to develop a new, commercially-available source based on the NIST spherical radiator ... H-P would like to anchor our comparisons to an internationally-recognized site ... . We support NIST's recent plans to build such a site ..."

Lowell Kolb
Senior Engineer
Hewlett-Packard Co.
Ft. Collins, CO

Integrated resistively tapered dipole and electrooptic modulator

Electromagnetic compatibility testing of large structures such as aircraft often requires intense fields requiring close proximity to high-power, pulsed sources. In these near-field regions neither the electric nor the magnetic components alone give an accurate measure of the total intensity. NIST has demonstrated a loop antenna with double gaps that simultaneously measures both the electric and magnetic components of the field. When coupled to appropriate instrumentation through optical fibers, it is ideally suited to accurately measuring the fields used in these high-intensity tests. NIST is building a field usable system which will further demonstrate the utility of such measurements and which will be a prototype transfer standard for simultaneous measurement of electric and magnetic fields.

MILESTONE: By 2001, demonstrate and document a transfer standard that can simultaneously measure both the electric and magnetic fields at frequencies up to 500 MHz.

NIST provides calibration services for commercial antennas in EMC testing. The frequencies of interest are often in the 1 to 400 MHz range, where the electromagnetic wavelength is too long for the tests to be done in existing enclosed test chambers. For these calibrations we use an open area test site (OATS), which consists of a smooth conducting, metallic ground plane about 50 m across which is situated in an area that, we assume, has a low ambient electromagnetic field background. Unfortunately, the rise in wireless telecommunications, ranging from commercial radio to cellular phones, has led to an increase in the ambient field levels and a resulting increase in measurement uncertainty they produce when an outdoor site is used. OATS are also used by commercially operated test laboratories and by numerous companies for testing their own products. Thus, they are located in many parts of the country and in many different ambient environments. The strength of the test fields are determined by measurements using standard antennas. As mentioned above, resistively- or electrically-coupled dipoles are often used for this purpose, but both are subject to particular error sources. NIST has fabricated a Standard RF Dipole system that avoids these sources of error and has a frequency response up to 1.5 GHz. Additional work needs to be done to complete this project.

MILESTONE: By 2000, perform error analysis and complete documentation for the standard RF dipole system. Demonstrate its utility by mapping the field amplitude and phase uniformity over a typical test volume at the NIST outdoor area test site.

Accomplishments

- Developed an RF dipole probe with electrically conducting leads that has been adopted as a standard by national test laboratories in England and Austria.
- Developed tuned, half-wave dipole antennas that cover a frequency range from 30 MHz to 1 GHz and have carefully calculated their response.
- Developed resistively tapered dipole probes with frequency responses up to 40 GHz. Probes based on this design are now being produced commercially by private industry.
- Developed a thermo-optic probe with millimeter-wave frequency response.
- Fabricated and tested probes with resistively-tapered dipoles and electro-optic coupling for measuring pulsed electromagnetic fields with bandwidths up to 5 GHz and amplitudes up to 40 kV/m.
- Fabricated and tested a near-field loop antenna with electro-optic coupling for simultaneous measurement of E- and H-fields.

- Fabricated a standard RF-dipole with electro-optic coupling which covers a frequency range from 10 MHz to 1.5 GHz.

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Electromagnetic Compatibility

Free-Field Time-Domain Electromagnetics

Technical Contact:
Robert T. Johnk
Phone: 303-497-3737

Staff-Years:
2.0 professionals
0.5 technician

Funding Sources:
NIST (60%)
Other (40%)

Project Goals

Provide accurate and efficient electromagnetic metrology covering a wide variety of applications such as antenna and sensor calibrations, EMC measurement facilities evaluation, shielding performance of commercial aircraft, non-destructive testing of electrical material properties, and precision standard-field generation.

Customer Needs

The burgeoning consumer electronics and wireless revolutions are placing a huge burden on the EMC regulatory communities. With the vast proliferation of electronics systems of all types and sizes, the emissions and immunity performance of these systems is of paramount importance, affecting issues such as health, safety, international trade, and U.S. competitiveness. The march of technology is relentless, and newer, more accurate, and more efficient metrological innovations need to be developed to keep pace with increasing performance, speed, and frequency. The free-field time-domain project will provide cutting-edge, innovative measurement techniques to support this revolution.

Technical Strategy

The project's primary focus is to perform ultrawideband electromagnetic measurements using swept-frequency or direct-pulse systems. Both time-domain and frequency-domain electromagnetic quantities can be extracted from our measurements. These systems exhibit high spatial resolution, which can be exploited to perform a wide variety of measurements and obtain useful information in a quick and accurate manner. We have developed ultrawideband systems to perform: (a) the extraction of materials properties from dielectric panels (low-loss & high-loss), (b) RF absorber evaluation at both normal and oblique incidence angles, (c) electromagnetic (EM) facility characterization (anechoic & semi-anechoic chambers, shielded rooms, reverberation chambers, and OATS facilities), (d) ultrawideband RCS measurement of the shielding performance of materials, and (e) electromagnetic penetration into commercial aircraft. We have performed antenna and sensor calibrations up to 14 GHz on our cone and ground-plane facility. We are currently designing the Co-Conical Field Generation System a closed system test cell capable of testing antennas, sensors, and probes from 10 MHz to 45 GHz. EM modeling and analysis is an integral part of our program. In addition to standard EM theory, many numerical techniques such as finite difference time domain (FDTD), finite element modeling (FEM), and variational methods are used to predict system performance and improve, as well as validate, our measurements. In addition, we are currently engaged in an aggressive effort to characterize the measurement uncertainties of our systems.

MILESTONE: By 2003, develop a rapid OATS evaluation measurement system that covers the 30 MHz to 6 GHz frequency range.

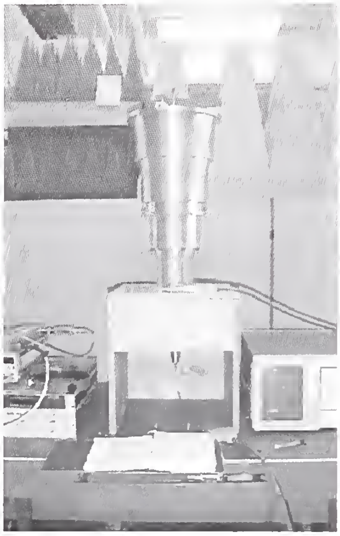
Evaluation of a commercial OATS facility using a portable NIST time-domain measurement system.

Information technology equipment is becoming faster and faster. In fact, fundamental bus data rates are currently above 1 GHz. In order to perform meaningful measurements of these devices, a frequency range of 30 MHz to 6 GHz must be covered. Current ANSI and IEC standards provide coverage only up to 1 GHz. There are currently no standards for test procedures and setups above 1 GHz! As operational frequencies increase further, the ability to characterize the measurement facilities becomes more critical. The use of NIST-developed free-field time-domain measurement techniques will play a key role in the development of new facility evaluation techniques and contribute significantly to the development of new international standards above 1 GHz.

MILESTONE: By 2002, develop a low-cost, ultra wideband measurement system for the performance evaluation of EMC measurement facilities.

"I believe that the experiments planned will be extremely useful both to Storage Tek and to U.S. industry ... could lead to improvements in future OATS designs, data that could be entered into a cost benefit analysis ... better hard data for identifying the site contributions to the overall OATS measurement uncertainty ..."

Monrad L. Monsen
Senior EMC Engineer
Product Compliance Test
Storage Technology Corp.
Louisville, CO



The Co-Conical Field Generation System.

Absorber-lined chamber testing using NIST-developed time domain fast-pulse measurement techniques.

Faster information technology equipment and wireless advances have vastly increased the frequency range over which emissions and immunity measurements must be performed. This, in turn, has increased the demand for quality measurements facilities. The quality of the facility and achievable measurement uncertainties are of paramount importance if good measurement fidelity is to be realized, particularly at higher frequencies. In order to assess these effects, NIST engineers are developing an ultrawideband time-domain measurement system for the evaluation of absorber-lined EMC chambers. The goal of this effort is to provide coverage and site analysis capability in the 30 MHz to 6 GHz frequency band. This system will use time-domain transmission measurements to compute the performance of absorber-lined chambers (both fully and semi-anechoic). Not only will this system provide fast and accurate chamber performance data, it will completely eliminate the need for a separate antenna calibration, cutting costs and time and improving efficiency.

MILESTONE: By 2001, develop a cone and ground plane sensor and antenna calibration facility that covers the 30 MHz to 18 GHz frequency range.

D-Dot Sensor calibration using a cone and ground plane standard-field generation system.

Accurate and reliable primary standards are going to play a key role in the development of next-generation measurement techniques. The central component of this program is a large new cone and ground-plane facility at NIST-Boulder. This facility will be capable of generating standard fields from 30MHz to 18GHz. This facility will also accommodate a wide variety of practical and useful measurements covering antenna and sensor calibrations, precision scattering measurements, and EMC shielding performance evaluations. This system will incorporate a moveable cone system that will permit the simulation of OATS environments for the development and verification of next-generation measurement techniques. New EMC measurement techniques will be essential if NIST is to solve critical measurement problems in the 21st century. This facility will also be a valuable tool for NIST participation in domestic and international EMC standards committees such as ANSI and IEC.

Accomplishments

The NIST free-field time-domain project has made significant advances during the decade of the 90's. Some of the more significant advances are:

- The use of NIST-developed time-domain measurement technology to evaluate the effects of electromagnetic radiation on commercial aircraft. This effort was sponsored by the FAA.
- Completion of feasibility study of the co-conical field generation system. A full turnkey facility development effort will be initiated in the near future. This system will be used as a standard-field generation system for probe calibrations in the 10MHz-45 GHz frequency range. This effort is currently being sponsored by the U.S. Air Force.
- The precision calibration of D-Dot sensors used in commercial aviation safety studies. NASA sponsored this effort.
- Using a free-space time-domain reflectometer to measure small samples of hybrid absorber used in commercial EMC testing chambers. This work has had a number of industrial sponsors: Lehman Chambers Inc., Hewlett-Packard, Lindgren RF Enclosures Inc, Advanced Electromagnetics Inc., Schaffner EMC, and IBEX/ Panashield.
- In situ measurements of the installed absorber system in a large commercial EMC emissions chamber. This work was sponsored by Lindgren RF Enclosures Inc.
- Time-domain site attenuation performance assessment of a pre-compliance EMC emissions and immunity chamber used for electronic analysis equipment development. This effort was sponsored jointly by IBEX/Panashield and the Hach Co.
- Using time-domain measurement systems to explore the possibility of assessing the effects of equipment shelters on OATS facilities. This effort was sponsored by Storage Technology Inc.

"...to offer our support to conduct in situ measurements inside anechoic chambers with time-domain that will later yield digitized data...Lehman Chambers has developed a 3-D Finite-Difference Time-Domain (FDTD) computer modeling program for the design and analysis of anechoic chambers for EMC applications. The work that NIST is intending to do will further validate our techniques and is of extreme interest to us."

Charles Devor
Lehman Chambers Inc.

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Electromagnetic Compatibility

Emissions and Immunity Metrology

Technical Contact:
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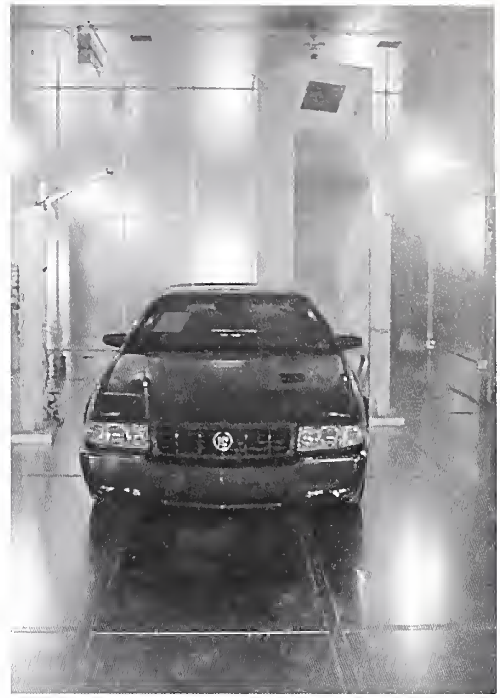
Phone: 303-497-5766

Staff-Years:
2.5 professionals
0.5 technician

Funding Sources:
NIST (70%)
Other (30%)

Project Goals

NIST develops and evaluates reliable measurement standards, test methods, and services to support the electromagnetic compatibility (EMC) needs of U.S. industry. These needs are related to electromagnetic emissions (intentional or unintentional signals transmitted by the device under test) and immunity (ability to resist external electromagnetic energy) of electronic devices, components and systems. The characterization of support hardware such as cables, connectors, enclosures, and absorbing or shielding material in an integral part of these measurements. Major challenges are to provide reliable and cost-effective test methods over a large frequency range (10 kHz to 40 GHz and, eventually, higher) and for large test volumes. The uncertainties of EMC and related measurements directly impact the competitiveness of U.S. manufacturers and the reliability of their products. NIST research can help quantify and, in some cases, reduce these measurement uncertainties. NIST expertise, focused on generating and measuring electromagnetic fields, serves as a fundamental resource for industry and government. The main objectives are to ensure harmony and international recognition of US measurements for trade, to provide physically correct test methods, to provide national calibration services, and to serve as an impartial expert body for resolving measurement inconsistencies.



Evaluation of Reverberation Chamber techniques for vehicle EMC testing

Customer Needs

U.S. industry must evaluate and control electromagnetic interference (EMI) which can impact economics and competitiveness (through trade restrictions and regulations), national security, health, and safety. U.S. industry pays 1 % to 10 % of total product cost and often suffers delays to market while trying to meet various EMC regulations and requirements. Industrial clients for NIST research, development, and measurement procedures are manufacturers of electronic equipment (or any system which employs electronic equipment), and test and product certification laboratories for EMI and EMC. Successful completion of this research should result in the development of measurement standards and techniques for EMI and EMC that are meaningful, technically practical, and cost-effective. A reduction in measurement uncertainties will lead to lower product development costs and facilitate acceptance of U.S. measurements by international regulating authorities. NIST, working with industry representatives, can help incorporate these techniques into voluntary standards by both U.S. and international standards organizations. Coordinated international standards based on sound metrology are vital for U.S. industry to participate fully in the global markets for electronic instrumentation and goods.

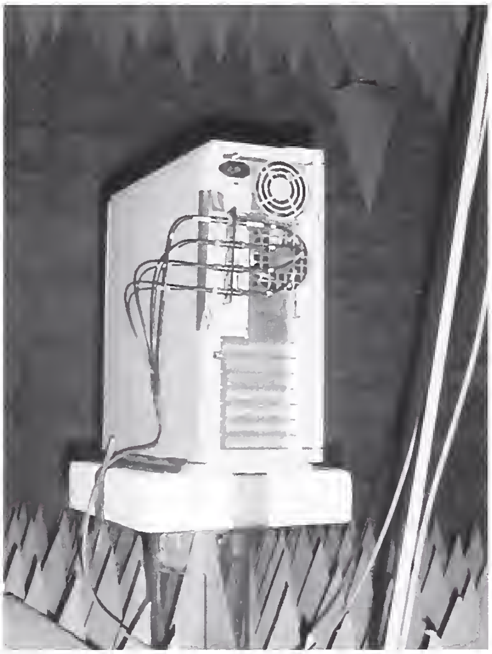
Technical Strategy

Research in EMI and EMC metrology impacts a very broad range of technology and products, including everything from consumer electronics, computers and wireless devices to large vehicles and aircraft. EMI and EMC concerns cover the entire radio-frequency spectrum, necessitating a variety of methodologies and test facilities. NIST research concentrates on developing techniques to generate electromagnetic fields for

test and calibrations, to measure fundamental electromagnetic parameters in essential segments of the spectrum, and to provide industry with measurement standards and services. The researchers draw on their collective experience in precision antenna measurements, electromagnetic field standards, time- and frequency-domain research, probe and antenna design, modeling and statistical analysis, and instrumentation to develop and analyze EMI / EMC measurement techniques. The techniques must often meet contradictory goals: they must be accurate and thorough, yet practical and cost-effective; they must have a low uncertainty, yet require a minimum of time.

"I am writing to you to express General Motor's interest in the ongoing research conducted by NIST in the area of reverberation chambers. The technical information generated by this research has helped to increase the understanding of the immense capabilities of this technology and has, more importantly, helped to inform the electromagnetic community about the benefits this technology has to offer..."

R. Nelson
Senior Project Engineer
General Motors Corp.
North American Operation/EMC



Measuring the radiation characteristics of a typical device-under-test in the NIST anechoic chamber

Facilities for radiated electromagnetic field testing are expensive and it is important to fully utilize that investment. NIST researchers examine both the immunity and the emissions measurement capabilities of selected test techniques or facilities. A good example of a technique with a wide range of capabilities, including emissions, immunity, and shielding of materials, cables, gaskets, and connectors, is the reverberation chamber. NIST research is leading the development of reverberation chamber theory and test techniques. Industry and government have accessed this research through conferences and workshops, archival publications, NIST Technical Notes and reports, special tests and consultations, and NIST participation in committees writing measurement standards. The overall strategy for the EMI and EMC program can be summed up as follows:

Develop and evaluate reliable and cost-effective standards, test methods, and measurement services related to electromagnetic emission and immunity of electronic devices. This includes the critical characteristics of support hardware such as antennas, cables, connectors, enclosures, and absorbing material. We continue to focus this research in areas of significant potential benefits and wide applications, including reverberation techniques, transverse electromagnetic (TEM) structures, anechoic chambers, time-domain ranges, open area test site (OATS), and new innovative techniques.

MILESTONE: By 2001, develop and evaluate techniques for rapid evaluation/calibration of electromagnetic field sensors (probes) in a reverberation chamber.

Milestone: By 2002, develop techniques for characterizing the efficiency and other antenna parameters used as transducers in reverberation chambers and for EMC certification on OATS and semi-anechoic chambers.

Milestone: By 2002, develop and propose to standard committee(s) a procedure for measuring the shielding and leakage properties of cables and connectors.

Milestone: By 2003, analyze, refine, and optimize measurement procedures for emissions and immunity measurements in a reverberation chamber, publish recommended procedures and applications.

Milestone: By 2005, develop and validate efficient methods for the characterization and calibration of measurement facilities using both frequency-domain and time-domain techniques.

Milestone: By 2007, develop and validate theoretical and statistical models for the intercomparison of EMI / EMC measurement facilities and procedures.

Evaluate, rigorously quantify, and develop methods to reduce measurement uncertainties. Most EMI and EMC measurements have large uncertainties due to many sources of error, including insufficient sampling of the radiated fields, poor field uniformity, device-under-test directivity and repeatability, and others. There is often a desire to reduce the number of samples and thereby simplify or shorten the test. While this reduces the cost of the test, the reduction in the obtained data often results in higher uncertainties and ironically may require more expensive EMI measures in the product in order to pass emissions or immunity regulations. A careful evaluation of measurement uncertainties

can lead to more optimal measurements. This will help to reduce product development and manufacturing costs and increase competitiveness. As the uncertainties are better understood, the credibility of the technique improves and it is easier to gain acceptance of U.S. measurements by international EMI and EMC regulating bodies.

Milestone: By 2005, develop and validate statistical models for EMI and EMC testing procedures, and device-under-test directivity and failure distributions. These models, in turn, form a basis for the analysis of total measurement uncertainties.

Provide current research data and other technical inputs to U.S. and international standards development organizations with a goal to harmonize standards for EMI and EMC worldwide. NIST will continue active participation in various IEC, CISPR, ANSI, SAE and IEEE standards committees.

Milestone: By 2005, provide technical input and active participation to committees in order to realize the publication of reverberation measurement techniques and TEM structures for EMC applications in national and international standards documents.

Accomplishments

- NIST has recently refurbished the Open Area Test Site (OATS) and the anechoic chamber to support research in antenna and emissions measurement methods and uncertainties. These sites support several programs including antenna calibrations and field standards, probe and antenna development, and EMI / EMC metrology. We are also pursuing plans for future world-class electromagnetic research and measurement facilities.

- We have published several new technical notes and conference papers covering recent developments in the electromagnetic theory, statistical analysis, modeling, and calibration of reverberation chambers (see references).

- We participated in joint research with U.S. automobile manufacturers and the Navy to evaluate reverberation techniques for vehicle EMI / EMC testing. The research team tested the research vehicles in multiple facilities including reverberation chambers and semi-anechoic chambers. NIST performed facility calibration measurements, test procedure consultation, and data analysis for this research.

- A program is in progress to developed new measurement methods and hardware to characterize ultra-weak emitters. The presence of ambient noise makes the characterization and detection of weak emitters even more difficult. However, spherical near-field scanning theory has been extended to the case where the emissions of the desired source inside the measurement sphere can be separated from the noise due to undesired sources outside the measurement sphere.

  We use the intrinsic electric and magnetic dipole moments to characterize electrically small emitters. These dipole moments are difficult to measure for weak emitters, but a sensitive TEM-cell method has been analyzed and verified experimentally. We are also pursuing, theoretically and experimentally, further work on weak emitter detection with portable antennas.

- Participated in joint research with the Naval Research Laboratory for EMI and EMC testing of advanced radar transmit/receive modules.

- Technical information was provided to several EMC standards committees (IEC-CISPR, IEC-TC77, RTCA DO-160, and SAE) actively drafting measurement requirements for reverberation techniques.

- Developed statistical models describing typical imperfections, and improved the statistical models of the fields encountered in reverberation chambers. After an extensive evaluation of the new reverberation chamber facility at NASA Langley Research Center we were able to contribute significantly to better understanding of reverberation technology. We have been able to identify several sources of errors in determining the field parameters in a reverberation chamber. These included antenna efficiency and other antenna effects, problems with inadequate mixing due to poor paddle design, direct coupling between the antennas, and errors in the formulas used to predict the fields. After completing several billion measurements in several different reverberation chambers, we have been able to develop new measurement and analysis techniques, significantly improving measurement accuracy and reducing uncertainties. We are now able to discern effects in the chamber performance on the order of less than one dB.

- Received Best Symposium Paper Award at the 1999 IEEE EMC Symposium, Seattle WA.
- Received Best Symposium Paper Award at the 1997 IEEE EMC Symposium, Austin TX.

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January 2000

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